

References

- Andreev, A.A., Pierau, R., Kalugin, I.A., Daryin, A.V., Smolyaninova, L.G., and Diekmann, B. 2007. Environmental changes in the northern Altai during the last millennium documented in Lake Teletskoye pollen record. *Quaternary Research* **67**: 394–399.
- Briffa, K.R. 2000. Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quaternary Science Reviews* **19**: 87–105.
- Butvilovskii, V.V. 1993. *Paleogeography of the Late Glacial and Holocene on Altai*. Tomsk University, Tomsk.
- Chen, F.H., Chen, J.H., Holmes, J., Boomer, I., Austin, P., Gates, J.B., Wang, N.L., Brooks, S.J., and Zhang, J.W. 2010. Moisture changes over the last millennium in arid central Asia: a review, synthesis and comparison with monsoon region. *Quaternary Science Reviews* **29**: 1055–1068.
- Demezhko, D.Yu. and Shchapov, V.A. 2001. 80,000 years ground surface temperature history inferred from the temperature-depth log measured in the superdeep hole SG-4 (the Urals, Russia). *Global and Planetary Change* **29**: 167–178.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Esper, J. and Schweingruber, F.H. 2004. Large-scale treeline changes recorded in Siberia. *Geophysical Research Letters* **31**: 10.1029/2003GL019178.
- Gamache, I. and Payette, S. 2005. Latitudinal response of subarctic tree lines to recent climate change in Eastern Canada. *Journal of Biogeography* **32**: 849–862.
- Golovanova, I.V., Sal'manova, R.Yu., and Demezhko, D.Yu. 2012. Climate reconstruction in the Urals from geothermal data. *Russian Geology and Geophysics* **53**: 1366–1373.
- Grace, J., Berninger, F., and Nagy, L. 2002. Impacts of climate change on the tree line. *Annals of Botany* **90**: 537–544.
- Hantemirov, R.M. and Shiyatov, S.G. 2002. A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia. *The Holocene* **12**: 717–726.
- Helama, S., Lindholm, M., Timonen, M., and Eronen, M. 2004. Dendrochronologically dated changes in the limit of pine in northernmost Finland during the past 7.5 millennia. *Boreas* **33**: 250–259.
- Hiller, A., Boettger, T., and Kremenetski, C. 2001. Medieval climatic warming recorded by radiocarbon dated alpine tree-line shift on the Kola Peninsula, Russia. *The Holocene* **11**: 491–497.
- Huang, X., Oberhansli, H., von Suchodoletz, H., and Sorrel, P. 2011. Dust deposition in the Aral Sea: implications for changes in atmospheric circulation in central Asia during the past 2000 years. *Quaternary Science Reviews* **30**: 3661–3674.
- Jacoby, G.C., D'Arrigo, R.D., and Davaajats, T. 1996. Mongolian tree rings and 20th century warming. *Science* **273**: 771–773.
- Kallio, P. 1975. Reflections on the adaptations of organisms to the northern forest limit in Fennoscandia. Paper Presented at the Circumpolar Conference on Northern Ecology, National Research Council, Ottawa, Canada.
- Kalugin, I., Daryin, A., Smolyaninova, L., Andreev, A., Diekmann, B., and Khlystov, O. 2007. 800-yr-long records of annual air temperature and precipitation over southern Siberia inferred from Teletskoye Lake sediments. *Quaternary Research* **67**: 400–410.
- Kalugin, I., Selegei, V., Goldberg, E., and Seret, G. 2005. Rhythmic fine-grained sediment deposition in Lake Teletskoye, Altai, Siberia, in relation to regional climate change. *Quaternary International* **136**: 5–13.
- Kremenetski, K.V., Boettger, T., MacDonald, G.M., Vaschalova, T., Sulerzhitsky, L., and Hiller, A. 2004. Medieval climate warming and aridity as indicated by multiproxy evidence from the Kola Peninsula, Russia. *Palaeogeography and Palaeoclimate* **209**: 113–125.
- Krenke, A.N. and Chernavskaya, M.M. 2002. Climate changes in the preinstrumental period of the last millennium and their manifestations over the Russian Plain. *Izvestiya, Atmospheric and Oceanic Physics* **38**: S59–S79.
- Kullmann, L. 1981. Pattern and process of present tree-limits in the Tarna region, southern Swedish Lapland. *Fennia* **169**: 25–38.
- Kullmann, L. 1986. Late Holocene reproductional patterns of *Pinus sylvestris* and *Picea abies* at the forest limit in central Sweden. *Canadian Journal of Botany* **64**: 1682–1690.
- Lloyd, A.H. and Fastie, C.L. 2003. Recent changes in treeline forest distribution and structure in interior Alaska. *Ecoscience* **10**: 176–185.
- Lloyd, A.H., Rupp, T.S., Fastie, C.L., and Starfield, A.M. 2003. Patterns and dynamics of tree line advance on the Seward Peninsula, Alaska. *Journal of Geophysical Research* **108**: 10.1029/2001JD000852.

Observations: Temperature Records

- MacDonald, G.M., Kremenetski, K.V., and Beilman, D.W. 2008. Climate change and the northern Russian treeline zone. *Philosophical Transactions of the Royal Society B* **363**: 2285–2299.
- Mackay, A.W., Ryves, D.B., Battarbee, R.W., Flower, R.J., Jewson, D., Rioual, P., and Sturm, M. 2005. 1000 years of climate variability in central Asia: assessing the evidence using Lake Baikal (Russia) diatom assemblages and the application of a diatom-inferred model of snow cover on the lake. *Global and Planetary Change* **46**: 281–297.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Matul, A.G., Khusid, T.A., Mukhina, V.V., Chekhovskaya, M.P., and Safarova, S.A. 2007. Recent and late Holocene environments on the southeastern shelf of the Laptev Sea as inferred from microfossil data. *Oceanology* **47**: 80–90.
- Mazepa, V.S. 2005. Stand density in the last millennium at the upper tree-line ecotone in the Polar Ural Mountains. *Canadian Journal of Forest Research* **35**: 2082–2091.
- Morin, A. and Payette, S. 1984. Expansion recente du meleze a la limite des forets. (Quebec nordique). *Canadian Journal of Botany* **62**: 1404–1408.
- Naurzbaev, M.M. and Vaganov, E.A. 2000. Variation of early summer and annual temperature in east Taymir and Putoran (Siberia) over the last two millennia inferred from tree rings. *Journal of Geophysical Research* **105**: 7317–7326.
- Panin, A.V. and Nefedov, V.S. 2010. Analysis of variations in the regime of rivers and lakes in the Upper Volga and Upper Zapadnaya Dvina based on archaeological-geomorphological data. *Water Resources* **37**: 16–32.
- Panyushkina, I.P., Adamenko, M.F., and Ovchinnikov, D.V. 2000. Dendroclimatic net over Altai Mountains as a base for numerical paleogeographic reconstruction of climate with high time resolution. In: *Problems of Climatic Reconstructions in Pleistocene and Holocene 2*. Institute of Archaeology and Ethnography, Novosibirsk, pp. 413–419.
- Payette, S. 2007. Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. *Ecology* **88**: 770–780.
- Payette, S., Filion, L., Delwaide, A., and Begin, C. 1989. Reconstruction of tree-line vegetation response to long-term climate change. *Nature* **341**: 429–432.
- Shiyatov, S.G. 1992. The upper timberline dynamics during the last 1100 years in the Polar Ural mountains. In: Frenzel, B. (Ed.) *Oscillations of the Alpine and Polar Tree Limits in the Holocene*. Fischer, Stuttgart, Germany, pp. 195–203.
- Shiyatov, S.G. 1993. The upper timberline dynamics during the last 1100 years in the Polar Ural Mountains. *European Palaeoclimate and Man* **4**: 195–203.
- Shiyatov, S.G. 2003. Rates of in the upper treeline ecotone in the Polar Ural Mountains. *Pages Newsletter* **11**: 8–10.
- Sidorova, O.V., Vaganov, E.A., Naurzbaev, M.M., Shishov, V.V., and Hughes, M.K. 2007. Regional features of the radial growth of larch in North Central Siberia according to millennial tree-ring chronologies. *Russian Journal of Ecology* **38**: 90–93.
- Smolyaninova, L.G., Kalugin, I.A., and Daryin, A.V. 2004. Technique of receiving empiri-mathematical interdependence models between climatic parameters and litologi-geochemical character of bottom deposits. *Computer Technology* **9**: *Mathematic, Mechanic, Computing* **3**: 43–46.
- Solomina, O. and Alverson, K. 2004. High latitude Eurasian paleoenvironments: introduction and synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology* **209**: 1–18.
- Tranquillini, W. 1979. *Physiological Ecology of the Alpine Timberline*. Springer-Verlag, Berlin, Germany.
- Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive north Atlantic oscillation mode dominated the medieval climate anomaly. *Science* **324**: 78–80.
- Veelenturf, L.P.J. 1995. Analysis and applications of artificial neural networks. Prentice-Hall.
- Yang, B., Brauning, A., Johnson, K.R., and Shi, Y.F. 2002. General characteristics of temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 10.1029/2001GL014485.

4.2.4.4 Other Asian Countries

In addition to China, Russia, and Japan, the MWP has been identified in several other parts of Asia. Schilman *et al.* (2001), for example, analyzed foraminiferal oxygen and carbon isotopes, together with physical and geochemical properties of sediments, contained in two cores extracted from the bed of the southeastern Mediterranean Sea off the coast of Israel, where they found evidence for the MWP centered on AD 1200. They note there is an

abundance of other well-documented evidence for the existence of the MWP in the Eastern Mediterranean, including, they write, “high Saharan lake levels (Schoell, 1978; Nicholson, 1980), high Dead Sea levels (Issar *et al.*, 1989, 1991; Issar, 1990, 1998; Issar and Makover-Levin, 1996), and high levels of the Sea of Galilee (Frumkin *et al.*, 1991; Issar and Makover-Levin, 1996),” in addition to “a precipitation maximum at the Nile headwaters (Bell and Menzel, 1972; Hassan, 1981; Ambrose and DeNiro, 1989) and in the northeastern Arabian Sea (von Rad *et al.*, 1999).”

Schilman *et al.* (2002) analyzed high-resolution $\delta^{18}\text{O}$ values from a speleothem in Soreq Cave, central Israel (31°45'N, 35°03'E), as well as from planktonic foraminifera in two marine sediment cores retrieved just off the Ashdod coast (31°56.41'N, 34°22.13'E and 31°56.61'N, 34°19.79'E), to obtain a record of climate in this region over the past 3,600 years. The $\delta^{18}\text{O}$ values of the speleothem and marine cores showed “striking similarity” over the period of study, according to Schilman *et al.*, and they were determined to be primarily representative of historic changes in precipitation. Over the 3,600-year record, six major precipitation intervals were noted, three that were relatively wet and three that were relatively dry. The peaks of the humid events occurred at 3,200, 1,300, and 700 yr BP, the latter of which was said by the researchers to be “associated with the global MWP humid event.”

Cini Castagnoli *et al.* (2005) extracted a $\delta^{13}\text{C}$ profile of *Globigerinoides ruber* from a shallow-water core in the Gulf of Taranto (39°45'53"N, 17°53'33"E) to produce a high-precision record of climate variability over the past two millennia, after which it was statistically analyzed, together with a second two-millennia-long tree-ring record obtained from Japanese cedars (Kitagawa and Matsumoto, 1995), for evidence of recurring cycles using Singular Spectrum Analysis and Wavelet Transform. Plots of both records revealed the Dark Ages Cold Period (~400–800 AD), the Medieval Warm Period (~800–1200 AD), the Little Ice Age (~1500–1800 AD), and the Current Warm Period, the roots of which can be traced to an upswing in temperature that began in the depths of the Little Ice Age “about 1700 AD.”

Both records were compared with a 300-year record of sunspots. Results of the statistical analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity, plus a second multidecadal oscillation (of about 93 years for the shallow-water *G. ruber* series and 87 years for the

tree-ring series) in phase with the amplitude modulation of the sunspot number series over the last 300 years. According to the three researchers, the overall phase agreement between the two climate reconstructions and the variations in the sunspot number series “favors the hypothesis that the [multidecadal] oscillation revealed in $\delta^{13}\text{C}$ from the two different environments is connected to the solar activity,” suggesting a solar forcing was at work in both terrestrial and oceanic domains over the past two millennia.

Li *et al.* (2006) conducted palynological analyses of two sediment cores taken from the Song Hong (Red River) Delta, Vietnam (~20.26°N, 106.52°E) to reconstruct climate variations there throughout the Holocene. As indicated by an abundance of taxa well adapted to tropical and subtropical environments, they conclude the Medieval Warm Period (~AD 500–1330) was warmer than the current climate.

Kaniewski *et al.* (2011) write, “according to model-based projections, the northern Arabian Peninsula, a crossroad between Mediterranean, continental and subtropical climates, will be extremely sensitive to greenhouse warming,” citing the work of Alpert *et al.* (2008). They also note, “insights into past climate variability during historical periods in such climate hotspots are of major interest to estimate if recent climate trends are atypical or not over the last millennium,” but “few palaeo-environmental records span the MCA [Medieval Climate Anomaly] and LIA [Little Ice Age] in the Middle East.” Based on an analysis of pollen types and quantities found in a 315-cm sediment core retrieved from alluvial deposits within the floodplain of a spring-fed valley located at 35°22'13.16"N, 35°56'11.36"E in the coastal Syrian lowland, Kaniewski *et al.* converted the pollen data into Plant Functional Types (PFTs) that allowed them to construct pollen-derived Biomes (PdBs) similar to the regional studies of Tarasov *et al.* (1998). They were then able to relate the ratio of PdB warm steppe (WAST) divided by PdB cool steppe (COST) to local temperature, as also had been done a decade earlier by Tarasov *et al.* (1998).

The seven scientists state their WAST/COST record “indicates that temperature changes in coastal Syria are coherent with the widely documented warming during the MCA and cooling during the LIA,” assigning the first of these epochs to the period of approximately AD 1000 to 1230 and the latter to approximately AD 1580 to 1850. Regarding the Current Warm Period, they state, “modern warming

Observations: Temperature Records

appears exceptional in the context of the past 1250 years, since only three warm peaks of similar amplitude are registered during the High Middle Ages.” However, they conclude, the “three peaks centered on ca. 1115, 1130 and 1170 cal yr AD suggest similar or warmer temperatures compared to AD 2000.” The plot of their WAST/COST record (Figure 4.2.4.4.1) shows the warmth of the first and last of these peaks was essentially identical to that centered on the end of the last century (AD 2000), and the central peak at AD 1130 was the warmest.

The findings of Kaniewski *et al.* thus reveal recent climate trends in the region of Syria they studied are not atypical over the last millennium, although they do not say so in their study. Earth’s current level of warmth need not be attributed to the current high level of the air’s CO₂ content; the peak warmth of the MWP was greater than it has been over the past couple of decades yet the air’s CO₂ concentration was approximately 100 ppm less than it is today.

transition from the depth of the Dark Ages Cold Period to the midst of the Medieval Warm Period. After that, Kar *et al.*’s data indicate the climate “became much cooler,” indicative of its transition to Little Ice Age conditions, and during the last 200 years there has been a rather steady warming, as shown by Esper *et al.* (2002a) to have been characteristic of the entire Northern Hemisphere.

Feng and Hu (2005) acquired decadal surface air temperatures for the last two millennia from ice core and tree-ring data obtained at five locations on the Tibetan Plateau. These data revealed the late twentieth century was the warmest period in the past two millennia at two of the sites (Dasuopu, ice core; Dundee, ice core), but not at the other three sites (Dulan, tree ring; South Tibetan Plateau, tree ring; Guilya, ice core). At Guilya, for example, the data indicated it was significantly cooler in the final two decades of the twentieth century than for most of the first two centuries of the record, which comprised the latter part of the Roman Warm Period. At the South

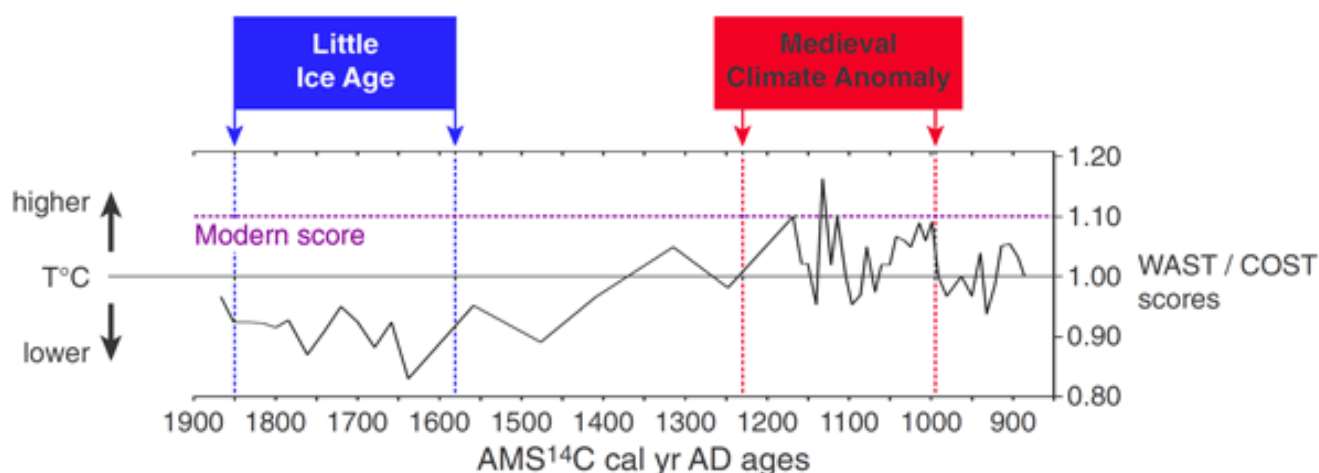


Figure 4.2.4.4.1. The 880-1870 cal yr AD warm-cool ratio WAST/COST temperature reconstruction of Kaniewski, D., Van Campo, E., Paulissen, E., Weiss, H., Bakker, J., Rossignol, I., and Van Lerberghe, K. 2011. The medieval climate anomaly and the little Ice Age in coastal Syria inferred from pollen-derived palaeoclimatic patterns. *Global and Planetary Change* 78: 178–187, Figure 5.

Kar *et al.* (2002) explored the nature of climate change in India as preserved in the sediment profile of an outwash plain two to three km from the snout of the Gangotri Glacier in the Uttarkashi district of Uttaranchal, Western Himalaya. Their data reveal a relatively cool climate between 2,000 and 1,700 years ago. From 1,700 to 850 years ago, there was what they called an “amelioration of climate” during the

Tibetan Plateau it was also significantly warmer over a full century near the start of the record, and at Dulan it was significantly warmer for the same portion of the Roman Warm Period plus two near-century-long portions of the Medieval Warm Period. These observations cast doubt on claims late twentieth century temperatures were unprecedented over the past two millennia, and they provide additional

evidence for the millennial-scale climatic oscillation that sequentially brought the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period.

Phadtare and Pant (2006) developed a 3,500-year palaeoclimate record of the Late Holocene using a study of pollen and organic matter content and the magnetic susceptibility of radiocarbon-dated samples from a peat deposit in the Kumaon Higher Himalaya of India (30°3'N, 70°56'E). "With an abrupt rise in temperature as well as moisture at ~AD 400," they write, "the climate suddenly turned warm and moist and remained so until ~AD 1260." This period, they note, is "generally referred to as the Medieval Warm Period in the Northern Hemisphere." The climate turned cold and dry over the ensuing century, but then warm and wet again, before turning "cold and moist during ~AD 1540–1730," stating the latter climate episode "represent[s] the Little Ice Age event in the Garhwal-Kumaon Himalaya."

Thereafter, the Indian researchers say, "the climate has been persistently wet with relatively higher temperatures until ca. AD 1940, followed by a cooling trend that continued till the present."

This dramatic modern cooling also is observed in the regional tree-ring record of Yadav *et al.* (2004), who used many long tree-ring series obtained from widely spaced Himalayan cedar (*Cedrus deodara* (Roxb.) G. Don) trees growing on steep slopes with thin soil cover to develop a temperature history of the western Himalayas for the period AD 1226–2000. "Since the 16th century," they write, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226–1500), reflecting unstable climate during the Little Ice Age (LIA)."

Yadav *et al.* note similar results have been obtained from juniper tree-ring chronologies from central Tibet (Braeuning, 2001), and "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." Yadav *et al.* report 1944–1953 was the warmest 10-year mean of the entire 775-year record, and "thereafter, temperatures decreased." This cooling, they note, "is in agreement with the instrumental records." Also, they state, "tree-ring based temperature reconstructions from other Asian mountain regions like Nepal (Cook *et al.*, 2003), Tibet and central Asia (Briffa *et al.*, 2001) also document cooling during [the] last decades of the 20th century."

The temperatures of the final two decades of Yadav *et al.*'s record appear to be as cold as those of any comparable period over the prior seven-and-a-half centuries, including the coldest periods of the Little Ice Age. This result, they indicate, is radically different from the temperature reconstruction of Mann and Jones (2003), which depicts "unprecedented warming in the 20th century."

Brauning and Griessinger (2006) analyzed $\delta^{13}\text{C}$ data obtained from wood cellulose of annual growth rings of long-lived juniper (*Juniperus tibetica*) trees growing at a site in east-central Tibet at approximately 31.8°N, 92.4°E, which were found to be significantly positively correlated with summer temperatures of the surrounding region. The authors found "warm and dry conditions during the Medieval Warm Period between AD 1200 and 1400." Their graph of the data reveals the peak temperature of the MWP to have been greater than the peak temperature of the CWP.

Chauhan (2006) derived abundance distributions of various types of pollen deposited over the past 1,300 years in a one-meter-deep sediment core retrieved from the alpine-region Naychhudwari Bog (77°43'E, 32°30'N) of Himachal Pradesh, northern India. Analyses revealed two broad climatic episodes of warm-moist and cold-dry conditions, the first covering the period AD 650 to 1200 and the second from AD 1500 onwards. "In the global perspective," the Indian scientist writes, the first period "is equivalent to the Medieval Warm Period, which has been witnessed in most parts of the world," while the second period "falls within the time-limit of [the] Little Ice Age."

In the first of these two periods, Chauhan remarks, "the alpine belt of this region experienced warm and moist climate [and] the glaciers receded and the tree-line ascended to higher elevations," suggesting the existence of a prior cooler and drier climate, the Dark Ages Cold Period. From AD 1500 onward, Chauhan writes, "the glaciers advanced and consequently the tree-line descended under the impact of [the] cold and dry climate in the region."

Bhattacharyya *et al.* (2007) developed a relative history of atmospheric warmth and moisture covering the last 1,800 years for the region surrounding Paradise Lake, located in the Northeastern Himalaya at approximately 27°30.324'N, 92°06.269'E, based on pollen and carbon isotopic ($\delta^{13}\text{C}$) analyses of a one-meter-long sediment profile obtained from a pit "dug along the dry bed of the lakeshore." Their climatic reconstruction revealed a "warm and moist

Observations: Temperature Records

climate, similar to the prevailing present-day conditions,” around AD 240, which would represent the last part of the Roman Warm Period, and another such period “warmer 1100 yrs BP (around AD 985) corresponding to the Medieval Warm Period.”

Chauhan and Quamar (2010) analyzed a 2-m-long sediment core retrieved from the Kiktiha Swamp of Central India (~23°N, 84°E) to develop temporal distributions of many types of plants, identifying three major climatic regimes over the past 1,650 years. The first of these regimes was described by the two researchers as “a warm and moist climate,” which “supported tropical deciduous Sal forests.” This interval “corresponds with the period of the Medieval Warm Period, which is known between AD 740 and 1150 (Lamb, 1977).” The second regime, from about AD 1250 to 1650, was mostly a “period of harsh climate” that “falls within the temporal range of [the] Little Ice Age.” It was followed by the third regime, another warm period that has now persisted for three centuries and resulted in “the revival of modern Sal forests.” It is not possible to determine from Chauhan and Quamar’s paper which of the two warm periods may have been the warmer.

Kotlia and Joshi (2013) examined a 3.55-meter-long sediment core extracted from Badanital Lake (30°29’50”N, 78°55’26”E) in the Garhwal Himalaya of India, finding “the imprints of four major global events”—the “4.2 ka event, Medieval Warm Period (MWP), Little Ice Age (LIA) and modern warming”—based on measurements and analyses of “major oxides and their ratios (CaO/MgO, CaO/TiO₂, MgO/TiO₂, Na₂O/TiO₂, TiO₂/Al₂O₃, Na₂O/K₂O and Fe₂O₃/TiO₂), major elements, chemical index of weathering, chemical index of alteration and loss on ignition.” They report the MWP “prevailed around 920–440 years BP,” concluding their work “adds to the growing evidence for the global extent of these events.”

Esper *et al.* (2002b) used more than 200,000 ring-width measurements obtained from 384 trees at 20 sites ranging from the lower to upper timberline in the Northwest Karakorum of Pakistan (35–37°N, 74–76°E) and Southern Tien Shan of Kirghizia (40°10’N, 72°35’E) to reconstruct regional patterns of climatic variations in Western Central Asia since AD 618. They found the Medieval Warm Period was firmly established and growing warmer by the early seventh century, and between AD 900 and 1000, tree growth was exceptionally rapid, at rates they say “cannot be observed during any other period of the last millennium.”

Between AD 1000 and 1200, growing conditions deteriorated, and at about 1500, minimum tree ring-widths were reached that persisted well into the seventeenth century. Toward the end of the twentieth century, ring-widths increased once again, but Esper *et al.* (2002b) report “the twentieth-century trend does not approach the AD 1000 maximum.” There is almost no comparison between the two periods, with the Medieval Warm Period being far more conducive to tree growth than the Current Warm Period. As the three researchers note, “growing conditions in the twentieth century exceed the long-term average, but the amplitude of this trend is not comparable to the conditions around AD 1000.”

Esper *et al.* (2003) processed several extremely long juniper ring width chronologies for the Alai Range of the western Tien Shan in Kirghizia in such a way as to preserve multi-centennial growth trends typically “lost during the processes of tree ring data standardization and chronology building (Cook and Kairiukstis, 1990; Fritts, 1976).” They used two techniques that maintained low frequency signals: long-term mean standardization (LTM) and regional curve standardization (RCS), as well as the more conventional spline standardization (SPL) technique that obscures (removes) long-term trends.

Carried back a full thousand years, the SPL chronologies depict significant interdecadal variations but no longer-term trends. The LTM and RCS chronologies, on the other hand, show long-term decreasing trends from the start of the record until about AD 1600, broad minima from 1600 to 1800, and long-term increasing trends from about 1800 to the present. Esper *et al.* (2003) report, “the main feature of the LTM and RCS Alai Range chronologies is a multi-centennial wave with high values towards both ends.”

This result has essentially the same form as the Northern Hemisphere extratropical temperature history of Esper *et al.* (2002a), depicting the existence of both the Little Ice Age and preceding Medieval Warm Period, which are nowhere to be found in the “hockey stick” temperature reconstructions of Mann *et al.* (1998, 1999) and Mann and Jones (2003). In addition, the work of Esper *et al.* (2002b)—especially the LTM chronology, which has a much smaller variance than the RCS chronology—depicts several periods in the first half of the last millennium that were warmer than any part of the last century. These periods include much of the latter half of the Medieval Warm Period and a good part of the first half of the fifteenth century, which also has been

found to have been warmer than it is currently by McIntyre and McKittrick (2003) and by Loehle (2004). Esper *et al.* (2003) remark, “if the tree ring reconstruction had been developed using ‘standard’ detrending procedures only, it would have been limited to inter-decadal scale variation and would have missed some of the common low frequency signal.”

Treydte *et al.* (2009) write “it is still uncertain whether the magnitude and rate of 20th century warming exceeds natural climate variability over the last millennium,” citing Esper *et al.* (2002a, 2005a, 2005b), Moberg *et al.* (2005), D’Arrigo *et al.* (2006), Frank *et al.* (2007), and Juckes *et al.* (2007). They developed “a millennium-long (AD 828–1998), annually resolved $\delta^{13}\text{C}$ tree-ring chronology from high-elevation juniper trees in northern Pakistan [35.74–36.37°N, 74.56–74.99°W] together with three centennial-long (AD 1900–1998) $\delta^{13}\text{C}$ chronologies from ecologically varying sites,” defining an “optimum correction factor” they deemed best-suited to remove non-climatic trends in order to “provide new regional temperature reconstructions derived from tree-ring $\delta^{13}\text{C}$, and compare those records with existing regional evidence.”

This analysis (see Figure 4.2.4.4.2) shows the 1990s were “substantially below MWP temperatures,” and their reconstruction “provides additional suggestions that High Asian temperatures during the MWP might have exceeded recent conditions,” which is also suggested by “ring-width data from living trees (Esper *et al.*, 2007).” Thus they “find indications for warmth during the Medieval Warm Period” that imply summer temperatures “higher than today’s mean summer temperature.”

Yoshioka *et al.* (2001) analyzed the carbon isotopic composition of sediment cores taken from the Dae-Am San high moor (38.22°N, 128.12°E), located on the north-facing slope of Mount Dae-Am, Korean Peninsula. They found upward increases in the $\delta^{13}\text{C}$ of organic carbon in the sediment core, reaching a maximum at around AD 1100. These findings, according to the authors, suggest the climate of the Korean Peninsula was “warm during the Medieval Warm Period,” adding, if their interpretation is correct, the Medieval Warm Period was likely a global event.

Park (2011) writes, “information produced by climate modeling has become progressively more

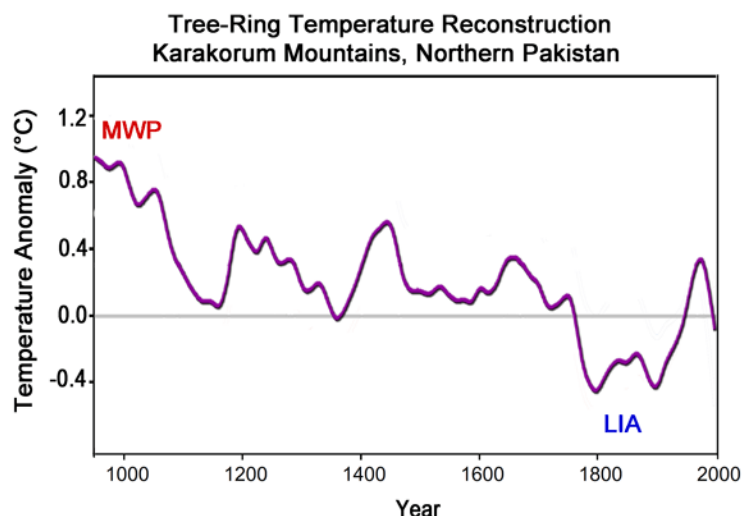


Figure 4.2.4.4.2. Proxy tree-ring temperature reconstruction from the Karakorum Mountains, Northern Pakistan. Adapted from Treydte, K.S., Frank, D.C., Saurer, M., Helle, G., Schleser, G.H., and Esper, J. 2009. Impact of climate and CO₂ on a millennium-long tree-ring carbon isotope record. *Geochimica et Cosmochimica Acta* **73**: 4635–4647.

important to understand past climate changes as well as to predict future climates.” The Korean researcher also observes, “to evaluate the reliability of such climate model results, quantitative paleoclimate data are essential.” In a study designed to obtain such data for a part of the world that has not been intensively studied, Park used modern surface pollen samples from the mountains along the east coast of Korea to derive pollen-temperature transfer functions, which were tested for robustness via detrended correspondence analysis and detrended canonical correspondence analysis, after which the best of these transfer functions was applied to the five fossil pollen records of Jo (1979), Chang and Kim (1982), Chang *et al.* (1987), Fuiki and Yasuda (2004), and Yoon *et al.* (2008), which were derived from four coastal lagoons of Korea’s east coast plus one high-altitude peat bog.

Park determined “the ‘Medieval Warm Period’, ‘Little Ice Age’ and ‘Migration Period’ were clearly shown,” the first of which was identified as having occurred between AD 700 and 1200, the next between AD 1200 and 1700, and the last as having occurred between AD 350 and 700. The earliest of these periods is commonly referred to as the Dark Ages Cold Period but sometimes described as the Migration Period, as Park reports it was a time “when people migrated southward in Europe because of deteriorating environmental conditions.” The

Observations: Temperature Records

graphical representation of Park's temperature reconstruction shows the peak temperature of the Medieval Warm Period was only slightly lower (by about 0.18°C) than the peak temperature of the Current Warm Period, which occurs at the end of the Korean temperature record.

Park's findings imply "the various late-Holocene climate shifts all occurred in the Korean peninsula at the same time as in other regions of the world," and modern-day warming on the Korean peninsula is only slightly greater than what occurred there in the Medieval Warm Period. It is evident from Park's temperature reconstruction that it may have been slightly warmer approximately 2,200 years ago than it was near the end of the twentieth century, suggesting there is nothing unusual or unnatural about Earth's current level of warmth.

References

- Alpert, P., Krichak, S.O., Shafir, H., Haim, D., and Osetinsky, I. 2008. Climatic trends to extremes employing regional modeling and statistical interpretation over the E. Mediterranean. *Global and Planetary Change* **63**: 163–170.
- Ambrose, S.H. and DeNiro, M.J. 1989. Climate and habitat reconstruction using stable carbon and nitrogen isotope ratios of collagen in prehistoric herbivore teeth from Kenya. *Quaternary Research* **31**: 407–422.
- Bell, B. and Menzel, D.H. 1972. Toward the observation and interpretation of solar phenomena. AFCRL F19628-69-C-0077 and AFCRL-TR-74-0357, Air Force Cambridge Research Laboratories, Bedford, MA, pp. 8–12.
- Bhattacharyya, A., Sharma, J., Shah, S.K., and Chaudhary, V. 2007. Climatic changes during the last 1800 yrs BP from Paradise Lake, Sela Pass, Arunachal Pradesh, Northeast Himalaya. *Current Science* **93**: 983–987.
- Braeuning, A. 2001. Climate history of Tibetan Plateau during the last 1000 years derived from a network of juniper chronologies. *Dendrochronologia* **19**: 127–137.
- Brauning, A. and Griessinger, J. 2006. Late Holocene variations in monsoon intensity in the Tibetan-Himalayan region—Evidence from tree rings. *Journal of the Geological Society of India* **68**: 485–493.
- Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Harris, I.C., Jones, P.D., Shiyatov, S.G., and Vaganov, E.A. 2001. Low frequency temperature variations from northern tree ring density network. *Journal of Geophysical Research* **106**: 2929–2941.
- Chang, C.-H. and Kim, C.-M. 1982. Late-Quaternary vegetation in the lake of Korea. *Korean Journal of Botany* **25**: 37–53.
- Chang, N.-K., Kim, Y.-P., O, I.-H., and Son, Y.-H. 1987. Past vegetation of Moor in Mt. Daeam in terms of the pollen analysis. *Korean Journal of Ecology* **10**: 195–204.
- Chauhan, M.S. 2006. Late Holocene vegetation and climate change in the alpine belt of Himachal Pradesh. *Current Science* **91**: 1562–1567.
- Chauhan, M.S. and Quamar, M.F. 2010. Vegetation and climate change in southeastern Madhya Pradesh during late Holocene, based on pollen evidence. *Journal of the Geological Society of India* **76**: 143–150.
- Cini Castagnoli, G., Taricco, C., and Alessio, S. 2005. Isotopic record in a marine shallow-water core: Imprint of solar centennial cycles in the past 2 millennia. *Advances in Space Research* **35**: 504–508.
- Cook, E.R. and Kairiukstis, L.A. 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kluwer, Dordrecht, The Netherlands.
- Cook, E.R., Krusic, P.J., and Jones, P.D. 2003. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. *International Journal of Climatology* **23**: 707–732.
- D'Arrigo, R., Wilson, R., and Jacoby, G. 2006. On the long-term context for late twentieth century warming. *Journal of Geophysical Research* **111**: 10.1029/2005JD006325.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002a. Low-frequency signals in long tree-ring chronologies and the reconstruction of past temperature variability. *Science* **295**: 2250–2253.
- Esper, J., Frank, D.C., Wilson, R.J.S., and Briffa, K.R. 2005a. Effect of scaling and regression on reconstructed temperature amplitude for the past millennium. *Geophysical Research Letters* **32**: 10.1029/2004GL021236.
- Esper, J., Frank, D.C., Wilson, R.J.S., Buntgen, U., and Treydte, K. 2007. Uniform growth trends among central Asian low- and high-elevation juniper tree sites. *Trees* **21**: 141–150.
- Esper, J., Schweingruber, F.H., and Winiger, M. 2002b. 1300 years of climatic history for Western Central Asia inferred from tree-rings. *The Holocene* **12**: 267–277.
- Esper, J., Shiyatov, S.G., Mazepa, V.S., Wilson, R.J.S., Graybill, D.A., and Funkhouser, G. 2003. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. *Climate Dynamics* **21**: 699–706.
- Esper, J., Wilson, R.J.S., Frank, D.C., Moberg, A., Wanner, H., and Luterbacher, J. 2005b. Climate: past ranges and future changes. *Quaternary Science Reviews* **24**: 2164–2166.

- Feng, S. and Hu, Q. 2005. Regulation of Tibetan Plateau heating on variation of Indian summer monsoon in the last two millennia. *Geophysical Research Letters* **32**: 10.1029/2004GL021246.
- Frank, D., Esper, J., and Cook, E.R. 2007. Adjustment for proxy number and coherence in a large-scale temperature reconstruction. *Geophysical Research Letters* **34**: 10.1029/2007GL030571.
- Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press, London, UK.
- Frumkin, A., Margaritz, M., Carmi, I., and Zak, I. 1991. The Holocene climatic record of the salt caves of Mount Sedom, Israel. *The Holocene* **1**: 191–200.
- Fujiki, T. and Yasuda, Y. 2004. Vegetation history during the Holocene from Lake Hyangho, northeastern Korea. *Quaternary International* **123–125**: 63–69.
- Hassan, F.A. 1981. Historical Nile floods and their implications for climatic change. *Science* **212**: 1142–1145.
- Issar, A.S. 1990. *Water Shall Flow from the Rock*. Springer, Heidelberg, Germany.
- Issar, A.S. 1998. Climate change and history during the Holocene in the eastern Mediterranean region. In: Issar, A.S. and Brown, N. (Eds.) *Water, Environment and Society in Times of Climate Change*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 113–128.
- Issar, A.S. and Makover-Levin, D. 1996. Climate changes during the Holocene in the Mediterranean region. In: Angelakis, A.A. and Issar, A.S. (Eds.) *Diachronic Climatic Impacts on Water Resources with Emphasis on the Mediterranean Region*, NATO ASI Series, Vol. I, 36, Springer, Heidelberg, Germany, pp. 55–75.
- Issar, A.S., Tsoar, H., and Levin, D. 1989. Climatic changes in Israel during historical times and their impact on hydrological, pedological and socio-economic systems. In: Leinen, M. and Sarnthein, M. (Eds.) *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 535–541.
- Issar, A.S., Govrin, Y., Geyh, M.A., Wakshal, E., and Wolf, M. 1991. Climate changes during the Upper Holocene in Israel. *Israel Journal of Earth-Science* **40**: 219–223.
- Jo, W.-R. 1979. Palynological studies on postglacial age in eastern coastal region, Korean peninsula. *Tohoku-Chiri* **31**: 23–55.
- Jukes, M.N., Allen, M.R., Briffa, K.R., Esper, J., Hegerl, G.C., Moberg, A., Osborn, T.J., and Weber, S.L. 2007. Millennial temperature reconstruction intercomparison and evaluation. *Climates of the Past* **3**: 591–609.
- Kaniewski, D., Van Campo, E., Paulissen, E., Weiss, H., Bakker, J., Rossignol, I., and Van Lerberghe, K. 2011. The medieval climate anomaly and the little Ice Age in coastal Syria inferred from pollen-derived palaeoclimatic patterns. *Global and Planetary Change* **78**: 178–187.
- Kar, R., Ranhotra, P.S., Bhattacharyya, A., and Sekar B. 2002. Vegetation vis-à-vis climate and glacial fluctuations of the Gangotri Glacier since the last 2000 years. *Current Science* **82**: 347–351.
- Kitagawa, H. and Matsumoto, E. 1995. Climatic implications of $\delta^{13}\text{C}$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.
- Kotlia, B.S. and Joshi, L.M. 2013. Late Holocene climatic changes in Garhwal Himalaya. *Current Science* **104**: 911–919.
- Lamb, H.H. 1977. *Climate: Present, Past and Future*. Methuen, London.
- Li, Z., Saito, Y., Matsumoto, E., Wang, Y., Tanabe, S., and Vu, Q.L. 2006. Climate change and human impact on the Song Hong (Red River) Delta, Vietnam, during the Holocene. *Quaternary International* **144**: 4–28.
- Loehle, C. 2004. Climate change: detection and attribution of trends from long-term geologic data. *Ecological Modelling* **171**: 433–450.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.
- McIntyre, S. and McKittrick, R. 2003. Corrections to the Mann *et al.* (1998) proxy data base and Northern Hemispheric average temperature series. *Energy and Environment* **14**: 751–771.
- Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low and high-resolution proxy data. *Nature* **433**: 613–617.
- Nicholson, S.E. 1980. Saharan climates in historic times. In: Williams, M.A.J. and Faure, H. (Eds.) *The Sahara and the Nile*, Balkema, Rotterdam, The Netherlands, pp. 173–200.
- Park, J. 2011. A modern pollen-temperature calibration

Observations: Temperature Records

data set from Korea and quantitative temperature reconstructions for the Holocene. *The Holocene* **21**: 1125–1135.

Phadtare, N.R. and Pant, R.K. 2006. A century-scale pollen record of vegetation and climate history during the past 3500 years in the Pinder Valley, Kumaon Higher Himalaya, India. *Journal of the Geological Society of India* **68**: 495–506.

Schilman, B., Ayalon, A., Bar-Matthews, M., Kagan, E.J., and Almogi-Labin, A. 2002. Sea-land paleoclimate correlation in the Eastern Mediterranean region during the late Holocene. *Israel Journal of Earth Sciences* **51**: 181–190.

Schilman, B., Bar-Matthews, M., Almogi-Labin, A., and Luz, B. 2001. Global climate instability reflected by Eastern Mediterranean marine records during the late Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **176**: 157–176.

Schoell, M. 1978. Oxygen isotope analysis on authigenic carbonates from Lake Van sediments and their possible bearing on the climate of the past 10,000 years. In: Degens, E.T. (Ed.) *The Geology of Lake Van, Kurtman*. The Mineral Research and Exploration Institute of Turkey, Ankara, Turkey, pp. 92–97.

Tarasov, P.E., Cheddadi, R., Guiot, J., Bottema, S., Peyron, O., Belmonte, J., Ruiz-Sanchez, V., Saadi, F., and Brewer, S. 1998. A method to determine warm and cool steppe biomes from pollen data; application to the Mediterranean and Kazakhstan regions. *Journal of Quaternary Science* **13**: 335–344.

Treydte, K.S., Frank, D.C., Saurer, M., Helle, G., Schleser, G.H., and Esper, J. 2009. Impact of climate and CO₂ on a millennium-long tree-ring carbon isotope record. *Geochimica et Cosmochimica Acta* **73**: 4635–4647.

von Rad, U., Schulz, H., Riech, V., den Dulk, M., Berner, U., and Sirocko, F. 1999. Multiple monsoon-controlled breakdown of oxygen-minimum conditions during the past 30,000 years documented in laminated sediments off Pakistan. *Palaeogeography, Palaeoclimatology, Palaeoecology* **152**: 129–161.

Yadav, R.R., Park, W.K., Singh, J., and Dubey, B. 2004. Do the western Himalayas defy global warming? *Geophysical Research Letters* **31**: 10.1029/2004GL020201.

Yoon, S.-O., Moon, Y.-R., and Hwang, S. 2008. Pollen analysis from the Holocene sediments of Lake Gyeongpo, Korea and its environmental implications. *Journal of the Geological Society of Korea* **44**: 781–794.

Yoshioka, T., Lee, J.-Y., Takahashi, H.A., and Kang, S.J. 2001. Paleoenvironment in Dae-Am San high moor in the Korean Peninsula. *Radiocarbon* **43**: 555–559.

Zhang, J. and Crowley, T.J. 1989. Historical climate records in China and reconstruction of past climates (1470–1970). *Journal of Climate* **2**: 833–849.

4.2.4.5 Australia and New Zealand

Numerous peer-reviewed studies reveal modern temperatures are not unusual, unnatural, or unprecedented. Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration for many millennia. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO₂ concentration remained at values approximately 30% lower than those of today.

This section highlights evidence from Australia and New Zealand, where much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; the Current Warm Period is simply a manifestation of its latest phase. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

Wilson *et al.* (1979) sought to compare the temperature record from New Zealand, which is “in the Southern Hemisphere and ... meteorologically unrelated to Europe,” with the climate record of England, where the MWP had been identified. They analyzed the ¹⁸O/¹⁶O profile from the core to the surface of a stalagmite obtained from a cave in New Zealand dated by the ¹⁴C method. They found the proxy temperature record provided by the stalagmite was broadly similar to the climate record of England, exhibiting a period in the early part of the past millennium about 0.75°C warmer than it was in the mid-twentieth century (see Figure 4.2.4.5.1). They conclude, “such climatic fluctuations as the Medieval Warm Period and Little Ice Age are not just a local European phenomenon.”

Eden and Page (1998) analyzed sediment cores from Lake Tutira, North Island, New Zealand (~39.23°S, 176.9°E) to reconstruct a history of major storms over the past 2,000 years. They found six well-defined and “clearly distinguishable” storm periods of

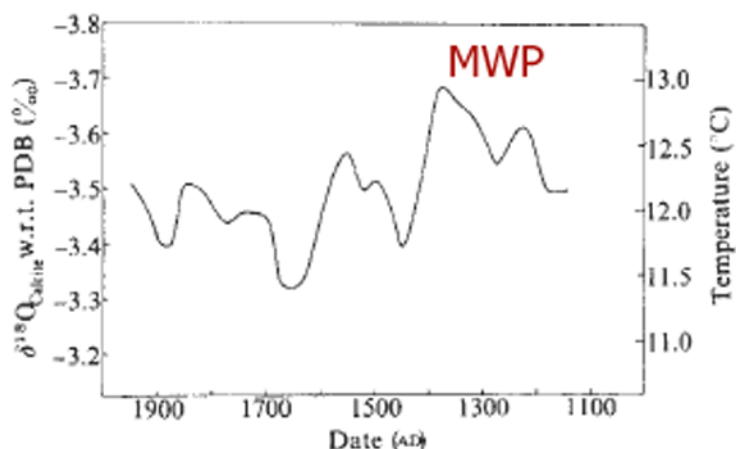


Figure 4.2.4.5.1. Proxy $^{18}\text{O}/^{16}\text{O}$ temperature reconstruction from a stalagmite in New Zealand. Adapted from Wilson, A.T., Hendy, C.H., and Reynolds, C.P. 1979. Short-term climate change and New Zealand temperatures during the last millennium. *Nature* **279**: 315–317.

the pre-instrumental era, illustrated in Figure 4.2.4.5.2. A seventh period based on data presented in Table 1 of the authors' paper has been added to indicate comparable storms of the modern era.

A comparison of these data with several independent climate proxies throughout the region led the authors to conclude stormy periods occurred

during times when the climate was warmer overall. They note, “the Mapara 2 period corresponds to sustained warm temperatures in the Tasmanian and Chilean tree-ring records which might indicate that the period represents a Southern Hemisphere-wide climate anomaly.” Additionally, “the Tufa Trig 1 period [AD 864–1014] corresponds to the early part of the Medieval Warm Period suggesting warmer temperatures occurred in New Zealand at this time.” Similar correlations were noted among the other storm periods, leading to the inference that given the large number of storm events during the RWP and MWP, as compared to the Current Warm Period (CWP), it is likely the CWP has been neither as warm nor as protracted as these earlier warm periods.

Williams *et al.* (2004) revise and build upon results derived by Williams *et al.* (1999) from stable isotope stratigraphy found in caves at Waitomo, located at 38.3°S latitude about 35 km from the west coast of the central North Island of New Zealand. They enhanced three existing speleothem (stalactite, stalagmite, or flowstone cave deposit) records “by adding another chronology, increasing the subsample resolution of existing

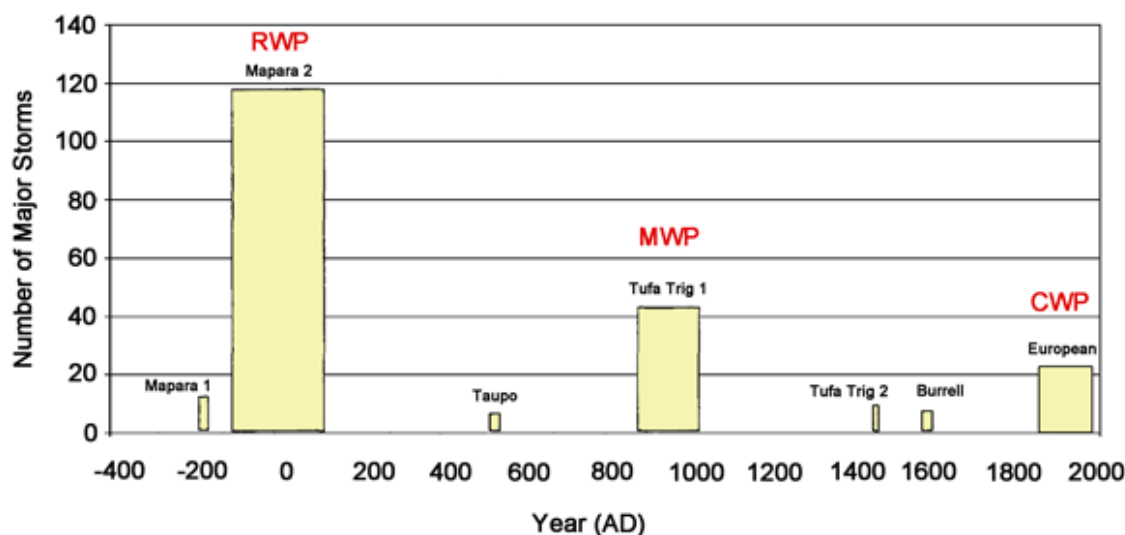


Figure 4.2.4.5.2. Number of major storms as determined from a sediment core from Lake Tutira, North Island, New Zealand. Adapted from Eden, D.N and Page, M.J. 1998. Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. *Palaeo-geography, Palaeoclimatology, Palaeoecology* **139**: 37–58.

Observations: Temperature Records

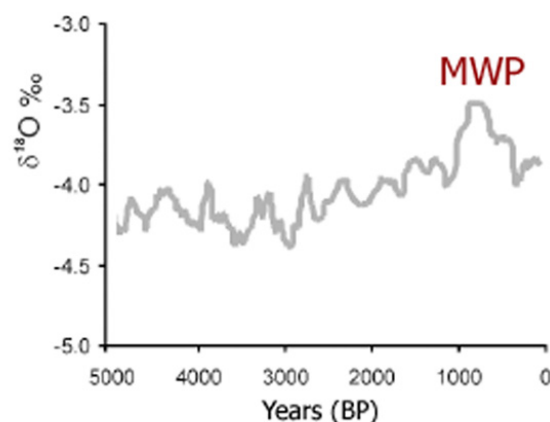


Figure 4.2.4.5.3. Composite $\delta^{18}\text{O}$ series obtained from four stalagmites found in caves at Waitomo, New Zealand. Adapted from Williams, P.W., King, D.N.T., Zhao, J.-X., and Collerson, K.D. 2004. Speleothem master chronologies: combined Holocene ^{18}O and ^{13}C records from the North Island of New Zealand and their palaeo-environmental interpretation. *The Holocene* **14**: 194–208.

records, and by much improving the temporal control of all chronologies by basing it entirely on uranium series TIMS dating.” Williams *et al.*’s improved speleothem master chronologies revealed a warmer-than-present late-Holocene warm peak located between 0.9 and 0.6 ka BP (see Figure 4.2.4.5.3), which they equated with the Medieval Warm Period of Europe, further noting this period “coincided with a period of Polynesian settlement (McGlone and Wilmshurst, 1999).” Thereafter, they report, temperatures “cooled rapidly to a trough about 325 years ago,” which they say corresponded to “the culmination of the ‘Little Ice Age’ in Europe.”

Lorrey *et al.* (2008) developed two master speleothem $\delta^{18}\text{O}$ records for New Zealand’s eastern North Island (ENI) and western South Island (WSI) for the period 2000 BC to about AD 1660 and 1825, respectively (see Figure 4.2.4.5.4). The WSI record was a composite chronology composed of data derived from four speleothems from Aurora, Calcite, Doubtful Xanadu, and Waiau caves, while the ENI record was a composite history derived from three speleothems from Disbelief and Te Reinga caves. For both the ENI and WSI $\delta^{18}\text{O}$ master speleothem histories, their warmest periods fell within the AD 900–1100 time interval of the MWP.

Wirmann *et al.* (2011) developed a multi-proxy approach to climate in New Caledonia in the southwest tropical Pacific, determining between *ca.* 2,640 and 2,000 cal yr BP, conditions were “drier and

cooler,” and subsequent observations linked wetter with warmer. They report, “between *ca.* 1250–500 cal yr BP the higher % of Rhizophoraceae and their peak around *ca.* 1080–750 cal yr BP underscore a mangrove belt development along the coastline.” This episode, they write, must be related to a wetter period and “may be related to a more global phenomenon such as the MWP in the Northern Hemisphere.”

The IPCC has rejected the existence of a global MWP, suggesting it was mostly limited in scope to countries surrounding the North Atlantic Ocean. The studies described above are of great importance to the ongoing global warming debate because they provide evidence the the MWP was a global phenomenon in which temperatures around the world were significantly warmer than they have been at any time subsequently. These studies confirm there is nothing unusual or unprecedented about Earth’s current level of warmth, with the necessary implication that the temperatures of the present cannot be attributed to the historical increase in the air’s CO_2 content.

References

- Eden, D.N. and Page, M.J. 1998. Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* **139**: 37–58.
- Lorrey, A., Williams, P., Salinger, J., Martin, T., Palmer, J., Fowler, A., Zhao, J.-X., and Neil, H. 2008. Speleothem stable isotope records interpreted within a multi-proxy framework and implications for New Zealand palaeoclimate reconstruction. *Quaternary International* **187**: 52–75.
- McGlone, M.S. and Wilmshurst, J.M. 1999. Dating initial Maori environmental impact in New Zealand. *Quaternary International* **59**: 5–16.
- Williams, P.W., King, D.N.T., Zhao, J.-X., and Collerson, K.D. 2004. Speleothem master chronologies: combined Holocene ^{18}O and ^{13}C records from the North Island of New Zealand and their palaeo-environmental interpretation. *The Holocene* **14**: 194–208.
- Williams, P.W., Marshall, A., Ford, D.C., and Jenkinson, A.N. 1999. Palaeoclimatic interpretation of stable isotope data from Holocene speleothems of the Waitomo district, North Island, New Zealand. *The Holocene* **9**: 649–657.
- Wilson, A.T., Hendy, C.H., and Reynolds, C.P. 1979. Short-term climate change and New Zealand temperatures during the last millennium. *Nature* **279**: 315–317.

Climate Change Reconsidered II

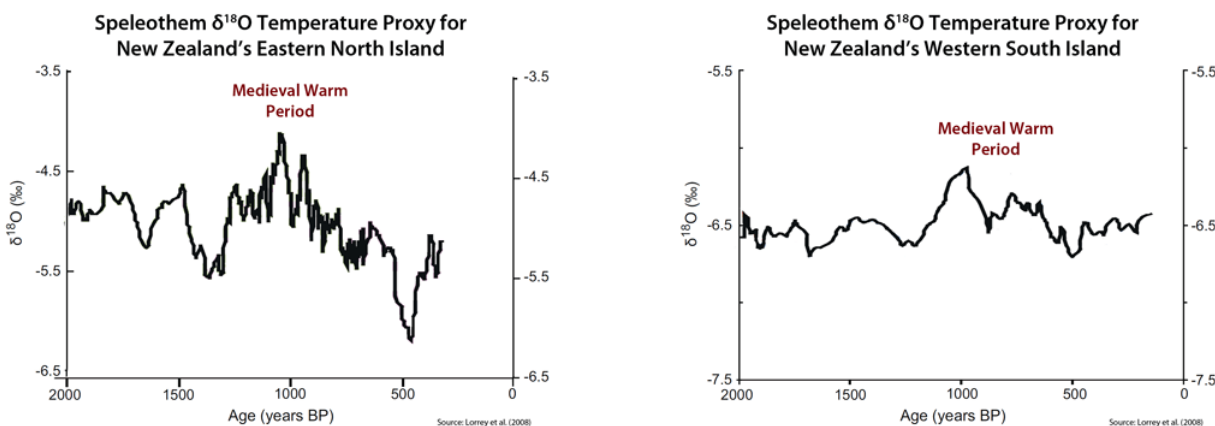


Figure 4.2.4.5.4. Composite speleothem $\delta^{18}\text{O}$ series obtained for New Zealand's eastern North Island and western South Island. Adapted from Lorrey, A., Williams, P., Salinger, J., Martin, T., Palmer, J., Fowler, A., Zhao, J.-X., and Neil, H. 2008. Speleothem stable isotope records interpreted within a multi-proxy framework and implications for New Zealand palaeoclimate reconstruction. *Quaternary International* **187**: 52–75.

Wirrmann, D., Semah, A.-M., Debenay, J.-P., and Chacornac-Rault, M. 2011. Mid- to late Holocene environmental and climatic changes in New Caledonia, southwest tropical Pacific, inferred from the littoral plain Gouaro-Deva. *Quaternary Research* **76**: 229–242.

4.2.4.6 Europe

The following subsections highlight evidence from Europe showing conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 concentration remained at values approximately 30 percent lower than they are today. Much of the material here focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing independent of carbon dioxide levels. The Current Warm Period is simply a manifestation of its latest phase.

4.2.4.6.1 Central

Filippi *et al.* (1999) obtained stable isotope data ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) from bulk carbonate and ostracode calcite in a radiocarbon-dated sediment core removed from Lake Neuchatel in the western Swiss Lowlands at the foot of the Jura Mountains, which they used to reconstruct the climatic history of that region over the

past 1,500 years (Figure 4.2.4.6.1.1). They determined mean annual air temperature dropped by about 1.5°C during the transition from the Medieval Warm Period (MWP) to the Little Ice Age (LIA). In addition, they state, “the warming during the 20th century does not seem to have fully compensated the cooling at the MWP-LIA transition” and during the Medieval Warm Period, mean annual air temperatures were “on average higher than at present.”

Bodri and Cermak (1999) derived individual

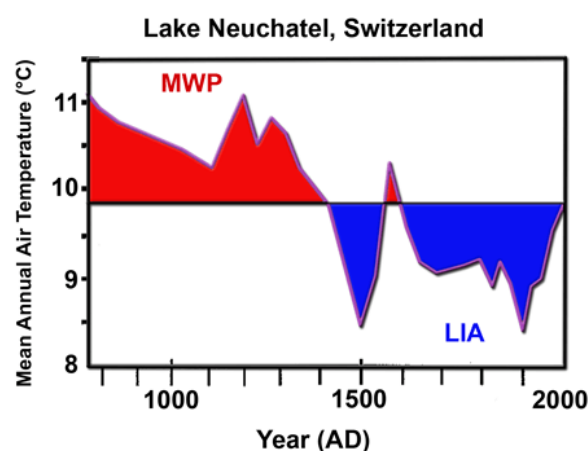


Figure 4.2.4.6.1.1. Temperature reconstruction obtained from sediment core removed from Lake Neuchatel in the western Swiss Lowlands. Adapted from Filippi, M.L., Lambert, P., Hunziker, J., Kubler, B., and Bernasconi, S. 1999. Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millennia. *Journal of Paleolimnology* **21**: 19–34.

Observations: Temperature Records

ground surface temperature histories from the temperature-depth logs of 98 boreholes in the Czech Republic. This work revealed, they write, “the existence of a medieval warm epoch lasting from 1100–1300 AD,” which they describe as “one of the warmest postglacial times.” They also note during the main phase of the Little Ice Age, from 1600–1700 AD, “all investigated territory was already subjected to massive cooling,” and “the observed recent warming may thus be easily a natural return of climate from the previous colder conditions back to a ‘normal.’”

Niggemann *et al.* (2003) studied petrographical and geochemical properties of three stalagmites found in the B7-Cave of Sauerland, Northwest Germany, from which they developed a climate history for the prior 17,600 years. These records, they write, “resemble records from an Irish stalagmite (McDermott *et al.*, 1999),” which also has been described by McDermott *et al.* (2001). The four researchers explicitly note their own records provide evidence for the existence of the Little Ice Age, the Medieval Warm Period, and the Roman Warm Period, which also implies the existence of what McDermott *et al.* (2001) called the Dark Ages Cold Period that separated the Medieval and Roman Warm Periods, as well as the unnamed cold period that preceded the Roman Warm Period. The wealth of corroborative information in these records (and many others) clearly suggests there is nothing unusual, unprecedented, or unexpected about the twentieth century warming that ushered in the Current Warm Period.

Bartholy *et al.* (2004) describe the work of Antal Rethly (1879–1975), a meteorologist, professor, and director of the National Meteorological and Earth Magnetism Institute of Hungary, who spent the greater portion of his long professional career collecting more than 14,000 historical records related to the climate of the Carpathian Basin. Rethly published in Hungarian a four-volume set of books, approximately 2,500 pages total, describing those records (Rethly, 1962, 1970; Rethly and Simon, 1999). Building upon this immense foundation, Bartholy *et al.* codified and analyzed the records collected by Rethly, noting, “in order to provide regional climate scenarios for any particular area, past climate tendencies and climatological extremes must be analyzed.” The three Hungarian scientists report “the warm peaks of the Medieval Warm Epoch and colder climate of the Little Ice Age followed by the recovery warming period can be detected in the

reconstructed temperature index time series.”

Mangini *et al.* (2005) developed a highly resolved record of temperature at high elevation, approximately 2,500 meters above sea level, during the past 2,000 years, using a precisely dated $\delta^{18}\text{O}$ record with better than decadal resolution derived from a stalagmite recovered from Spannagel Cave in the Central Alps of Austria. They applied to the data a transfer function they derived from a comparison of their $\delta^{18}\text{O}$ data with the reconstructed temperature history of post-1500 Europe developed by Luterbacher *et al.* (2004).

Mangini *et al.* found the lowest temperatures of the past two millennia, according to the new record, occurred during the Little Ice Age (AD 1400–1850), and the highest temperatures were found in the Medieval Warm Period (MWP: AD 800–1300). They write, the highest temperatures of the MWP were “slightly higher than those of the top section of the stalagmite (1950 AD) and higher than the present-day temperature.” At three points during the MWP, their data indicate temperature spikes in excess of 1°C above present (1995–1998) temperatures (see Figure 4.2.4.6.1.2).

Mangini *et al.* also report their temperature reconstruction compares well with reconstructions developed from Greenland ice cores (Muller and Gordon, 2000), Bermuda Rise ocean-bottom sediments (Keigwin, 1996), and glacier tongue advances and retreats in the Alps (Holzhauser, 1997; Wanner *et al.*, 2000), as well as with the Northern Hemispheric temperature reconstruction of Moberg *et al.* (2005). Considered together, Mangini *et al.* say the datasets “indicate that the MWP was a climatically distinct period in the Northern Hemisphere,” emphasizing “this conclusion is in strong contradiction to the temperature reconstruction by the IPCC, which only sees the last 100 years as a period of increased temperature during the last 2000 years.”

In a second refutation of an IPCC conclusion, Mangini *et al.* found “a high correlation between $\delta^{18}\text{O}$ and $\delta^{14}\text{C}$, that reflects the amount of radiocarbon in the upper atmosphere,” and this correlation “suggests that solar variability was a major driver of climate in Central Europe during the past 2 millennia.” They further report, “the maxima of $\delta^{18}\text{O}$ coincide with solar minima (Dalton, Maunder, Sporer, Wolf, as well as with minima at around AD 700, 500 and 300),” and “the coldest period between 1688 and 1698 coincided with the Maunder Minimum.” Also, in a linear-model analysis of the percent of variance of their full temperature reconstruction that is

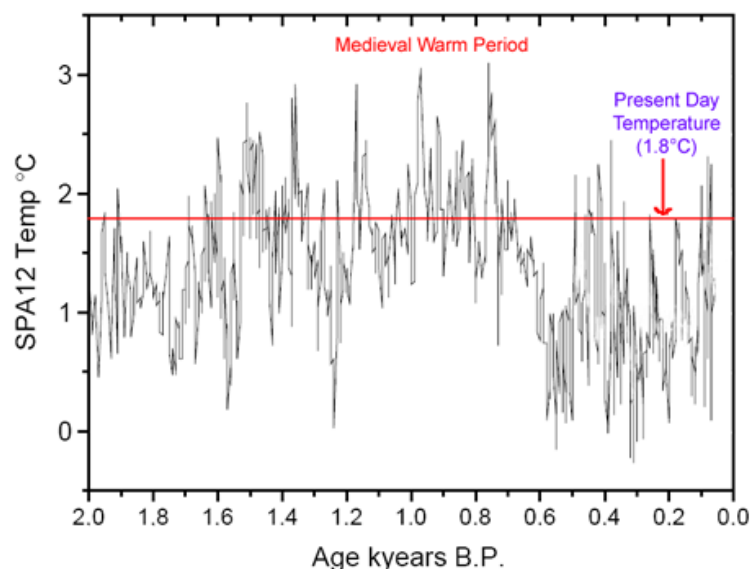


Figure 4.2.4.6.1.2. Temperature reconstruction from Spannagel Cave in the Central Alps of Austria. Adapted from Mangini, A., Spotl, C., and Verdes, P. 2005. Reconstruction of temperature in the Central Alps during the past 2000 yr from a $\delta^{18}\text{O}$ stalagmite record. *Earth and Planetary Science Letters* **235**: 741–751.

individually explained by solar and CO_2 forcing, they found the impact of the Sun was fully 279 times greater than that of the air's CO_2 concentration, noting “the flat evolution of CO_2 during the first 19 centuries yields almost vanishing correlation coefficients with the temperature reconstructions.”

These findings show the hockey stick temperature reconstruction of Mann *et al.* (1998, 1999), which has long been endorsed by the IPCC, does not reflect the true temperature history of the Northern Hemisphere over the past thousand years, nor does the hockey stick temperature reconstruction of Mann and Jones (2003) reflect the true temperature history of the world over the past two millennia. The Mann studies and the IPCC appear to be focusing on the wrong instigator of climate change over these periods; i.e., CO_2 in lieu of solar activity (see also Chapter 3, this volume).

Using the regional curve standardization technique applied to ring-width measurements from living trees and relict wood, Büntgen *et al.* (2005) developed a 1,052-year summer (June–August) temperature proxy from high-elevation Alpine environments in Switzerland and the western Austrian Alps (between $46^\circ 28'$ to $47^\circ 00' \text{N}$ and $7^\circ 49'$ to $11^\circ 30' \text{E}$). This temperature history revealed warm conditions from the beginning of the record in AD

951 to about AD 1350, which the five researchers associated with the Medieval Warm Period. Thereafter, temperatures declined and an extended cold period (the Little Ice Age) ensued, which persisted until approximately 1850, with one brief exception for a few short decades in the mid-to late-1500s, when there was an unusually warm period, the temperatures of which were exceeded only at the beginning and end of the 1,052-year record; i.e., during the Medieval and Current Warm Periods.

Holzhauser *et al.* (2005) presented high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, the northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest of all the glaciers in the European Alps.

Near the beginning of the time period studied, the three researchers report, “during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today,” noting “the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al.*, 2003).” After an intervening unnamed cold-wet phase when the glacier grew in both mass and length, “during the Iron/Roman Age Optimum between c. 200 BC and AD 50,” perhaps better known as the Roman Warm Period, the glacier again retreated and “reached today’s extent or was even somewhat shorter than today.” Next came the Dark Ages Cold Period, which they say was followed by “the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300.” The latter cold-wet phase was “characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60,” after which the glacier began its latest and still-ongoing recession in 1865. In addition, they state, documents from the fifteenth century AD indicate at some time during that hundred-year interval “the glacier was of a size similar to that of the 1930s,” when many parts of the world were as warm as, or even warmer than, they are today, in harmony with a growing body of evidence suggesting a “Little” Medieval Warm Period occurred during the fifteenth

Observations: Temperature Records

century within the broader expanse of the Little Ice Age.

Data pertaining to the Gorner glacier (the second largest of the Swiss Alps) and the Lower Grindelwald glacier of the Bernese Alps tell much the same story, as Holzhauser *et al.* report these glaciers and the Great Aletsch glacier “experienced nearly synchronous advances” throughout the study period.

The Swiss and French scientists report “glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity,” which in their estimation “suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlen, 1973; Magny, 1993; van Geel *et al.*, 1996; Bond *et al.*, 2001).” They conclude, “a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene.”

The current warmth of the region Holzhauser *et al.* studied has not yet resulted in a shrinkage of the Great Aletsch glacier equivalent to what it experienced during the Bronze Age Optimum of a little over three thousand years ago, nor what it experienced during the Roman Warm Period of two thousand years ago, suggesting there is nothing unusual or “unprecedented” about the region’s current warmth. Our modern warmth is occurring at just about the time one would expect it to occur, in light of the rather consistent time intervals that separated prior warm nodes of the millennial-scale climate oscillation that produced them. This suggests Earth’s current warmth, like that of prior Holocene warm periods, is likely solar-induced.

Chapron *et al.* (2005) note “millennial-scale Holocene climate fluctuations have been documented by lake level fluctuations, archaeological and palynological records for many small lakes in the Jura Mountains and several larger peri-alpine lakes.” They documented the Holocene evolution of Rhone River clastic sediment supply in Lake Le Bourget via sub-bottom seismic profiling and multidisciplinary analysis of well-dated sediment cores. This revealed, as they describe it, “up to five ‘Little Ice Age-like’ Holocene cold periods developing enhanced Rhone River flooding activity in Lake Le Bourget documented at *c.* 7200, 5200, 2800, 1600 and 200 cal. yr BP,” and “these abrupt climate changes were associated in the NW Alps with Mont Blanc glacier

advances, enhanced glaciofluvial regimes and high lake levels.” They also note “correlations with European lake level fluctuations and winter precipitation regimes inferred from glacier fluctuations in western Norway suggest that these five Holocene cooling events at 45°N were associated with enhanced westerlies, possibly resulting from a persistent negative mode of the North Atlantic Oscillation.”

Situated between these Little Ice Age-like periods would have been Current Warm Period-like conditions. The most recent of these prior warm regimes (the Medieval Warm Period) would have been centered at about AD 1100, while the prior one (the Roman Warm Period) would have been centered in the vicinity of 200 BC, which matches well with what is known about these warm regimes from many other studies.

Robert *et al.* (2006) analyzed assemblages of minerals and microfossils from a sediment core taken from the Berre coastal lagoon in southeast France (~43.44°N, 5.10°E) to reconstruct environmental changes in that region over the past 1,500 years. Their analyses revealed three distinct climatic intervals: a cold period that extended from about AD 400 to 900, a warm interval between about AD 980 and 1370, and a cold interval that peaked during the sixteenth and seventeenth centuries. These climatic intervals correspond, respectively, to the Dark Ages Cold Period, Medieval Warm Period (MWP), and Little Ice Age.

The team of eight researchers also found evidence of a higher kaolinite content in the sediment core during the MWP, which suggests, they write, “increased chemical weathering in relation to higher temperatures and/or precipitation.” In addition, they discovered the concentration of microfossils of the thermophilic taxon *Spiniferites bentorii* also peaked at this time, and this finding provides additional evidence the temperatures of that period were likely higher than those of the recent past.

Joerin *et al.* (2006) write, “the exceptional trend of warming during the twentieth century in relation to the last 1000 years highlights the importance of assessing natural variability of climate change.” The three Swiss researchers examined glacier recessions in the Swiss Alps over the past ten thousand years based on radiocarbon-derived ages of materials found in proglacial fluvial sediments of subglacial origin, focusing on subfossil remains of wood and peat. Combining their results with earlier data of a similar nature, they constructed a master chronology of Swiss

glacier fluctuations over the Holocene.

Joerin *et al.* report discovering “alpine glacier recessions occurred at least 12 times during the Holocene,” once again demonstrating the reality of the millennial-scale oscillation of climate that has reverberated throughout glacial and interglacial periods alike as far back in time as scientists have searched for the phenomenon. They also determined glacier recessions have been decreasing in frequency since approximately 7,000 years ago, and especially since 3,200 years ago, “culminating in the maximum glacier extent of the ‘Little Ice Age.’” Consequently, the warming of the twentieth century cannot be considered strange, since it represents a climatic rebound from the coldest period of the current interglacial, which was the coldest of the last five interglacials, according to Petit *et al.* (1999).

The last of the major glacier recessions in the Swiss Alps occurred between about 1,400 and 1,200 years ago according to Joerin *et al.*’s data, but it took place between 1,200 and 800 years ago, according to the data of Holzhauser *et al.* (2005) for the Great Aletsch Glacier. Joerin *et al.* say the two records need not be considered inconsistent with each other given the uncertainty of the radiocarbon dates. Their presentation of the Great Aletsch Glacier data also indicates the glacier’s length at about AD 1000, when there was fully 100 ppm less CO₂ in the air than there is today, was slightly less than its length in 2002, suggesting the peak temperature of the Medieval Warm Period likely was slightly higher than the peak temperature of the twentieth century.

Buntgen *et al.* (2006) developed an annually resolved mean summer (June–September) temperature record for the European Alps, covering the period AD 755–2004 and based on 180 recent and historic larch (*Larix decidua* Mill.) maximum latewood density series, created via the regional curve standardization method that preserves interannual to multi-centennial temperature-related variations. They found in this history the high temperatures of the late tenth, early thirteenth, and twentieth centuries and the prolonged cooling from ~1350 to 1700, or as they describe it, “warmth during medieval and recent times, and cold in between.” They report the coldest decade of the record was the 1810s, and even though the record extended through 2004, the warmest decade of the record was the 1940s. In addition, they observe, “warm summers seemed to coincide with periods of high solar activity, and cold summers vice versa.” They report comparing their temperature record with other regional- and large-scale

reconstructions “reveals similar decadal to longer-term variability,” causing them to conclude, “the twentieth-century contribution of anthropogenic greenhouse gases and aerosol remains insecure.”

Extending the work of Mangini *et al.* (2005), who had developed a 2,000-year temperature history of the central European Alps based on an analysis of $\delta^{18}\text{O}$ data obtained from stalagmite SPA 12 of Austria’s Spannagel Cave, Vollweiler *et al.* (2006) used similarly measured $\delta^{18}\text{O}$ data obtained from two adjacent stalagmites (SPA 128 and SPA 70) within the same cave to create a master $\delta^{18}\text{O}$ history covering the last 9,000 years, which Mangini *et al.* (2007) compared with the Hematite-Stained-Grain (HSG) history of ice-rafted debris in North Atlantic Ocean sediments developed by Bond *et al.* (2001), who had reported “over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum.”

Mangini *et al.* found a tight correspondence between the peaks and valleys of their $\delta^{18}\text{O}$ curve and the HSG curve of Bond *et al.*, concluding “the excellent match between the curves obtained from these two independent data sets gives evidence the $\delta^{18}\text{O}$ signal recorded in Spannagel cave reflects the intensity of the warm North Atlantic drift, disproving the assumption that the Spannagel isotope record is merely a local phenomenon,” and, therefore, their $\delta^{18}\text{O}$ curve “can reasonably be assumed to reflect non-local conditions,” implying it has wide regional applicability.

Mangini *et al.* next focus on why their $\delta^{18}\text{O}$ curve “displays larger variations for the last 2000 years than the multi-proxy record in Europe, which is mainly derived from tree-ring data” and “from low resolution archives (Mann *et al.*, 1998, 1999; Mann and Jones, 2003).” The most likely answer, they write, “is that tree-rings ... record the climate conditions during spring and summer,” whereas both the HSG and $\delta^{18}\text{O}$ curves “mirror winter-like conditions, which are only poorly recorded in tree-rings.”

Whereas the Mann *et al.* and Mann and Jones datasets do not reflect the existence of the Medieval Warm Period and Little Ice Age, the Spannagel Cave data do. Applying the calibration curve derived for SPA 12 by Mangini *et al.* (2005) to the new $\delta^{18}\text{O}$ curve, it can readily be determined the peak temperature of the Medieval Warm Period was approximately 1.5°C higher than the peak temperature of the Current Warm Period. In addition, the new dataset of Mangini *et al.* (2007) confirms the

Observations: Temperature Records

inference of Bond *et al.*'s finding that over the last 12,000 years virtually every centennial-scale cooling of the North Atlantic region "was tied to a solar minimum," demonstrating the datasets of Mann *et al.* and Mann and Jones fail to capture the full range of temperature variability over the past two millennia. The new dataset clearly depicts the existence of both the Little Ice Age and Medieval Warm Period, the latter of which is seen to have been substantially warmer over periods of centuries than the warmest parts of the twentieth century, almost certainly as a result of enhanced solar activity, and even though the air's CO₂ concentration during the Medieval Warm Period was at least 100 ppm less than it is today.

Schmidt *et al.* (2007) developed a 4,000-year climatic reconstruction by combining spring and autumn temperature anomaly reconstructions based on siliceous algae and pollen tracers found in a sediment core extracted from an Alpine lake (Oberer Landschitzsee; 47°14'52" N, 13°51'40" E) located at the southern slopes of the Austrian Central Alps just slightly above the present tree-line. They compared that reconstructed history with a similar time-scale reconstruction from another lake in the drainage area, local historical records, and other climate proxies on Alpine and Northern Hemispheric scales. They found "spring-temperature anomalies during Roman and Medieval times equaled or slightly exceeded the modern values and paralleled tree-line and glacier fluctuations." They identified "warm phases similar to present between ca. 850–1000 AD and 1200–1300 AD," which they say were "followed by climate deterioration at ca 1300 AD, which culminated during the Little Ice Age."

Schmidt *et al.* (2008) recreated the late-Holocene climate and land-use history for the region around an Austrian alpine lake, Oberer Landschitzsee (47°14'52" N, 13°51'40" E), by analyzing sediment grain size and the concentrations of major and trace elements and minerals in a 4,000-year sediment core recovered from the lake, together with autumn and spring temperature anomalies and ice cover estimated from selected pollen markers and a diatom and chrysophyte cyst thermistor-based regional calibration dataset. Their analysis identified the Roman Warm Period (300 BC to AD 400) and Medieval Warm Period (AD 1000 to AD 1600) and demonstrated "spring temperature anomalies during Roman and Medieval times equaled or slightly exceeded the modern values." They detected two other warm periods—1800 to 1300 BC and 1000 to 500 BC—as well as cooler periods between them,

including the Little Ice Age that occurred between the Medieval Warm Period and the Current Warm Period. In addition, they report, "four waves of alpine land use were coupled mainly with warm periods." They found the two warm periods that preceded the Current Warm Period were at least as warm as today.

Millet *et al.* (2009) write, "among biological proxies from lake sediments, chironomid [non-biting midge] assemblages are viewed as one of the most promising climatic indicators," and "the accuracy of chironomid assemblages for the reconstruction of Lateglacial temperatures is now broadly demonstrated." They developed a new chironomid-based temperature record from Lake Anterne (northern French Alps) covering the past two millennia, compared that reconstruction with other late-Holocene temperature records from Central Europe, and addressed the question of whether previously described centennial-scale climate events such as the Medieval Warm Period or Little Ice Age can be detected in this new summer temperature record, noting "at a hemispheric or global scale the existence of the LIA and MWP have been questioned."

The six scientists report they found evidence "of a cold phase at Lake Anterne between AD 400 and 680, a warm episode between AD 680 and 1350, and another cold phase between AD 1350 and 1900," stating these events were "correlated to the so-called 'Dark Age Cold Period' (DACP), the 'Medieval Warm Period' and the 'Little Ice Age.'" They note "many other climate reconstructions across western Europe confirm the existence of several significant climatic changes during the last 1800 years in Central Europe and more specifically the DACP, the MWP and the LIA." They also report the reconstructed temperatures of the twentieth century failed to show a return to MWP levels of warmth, but they attribute that to a breakdown of the chironomid-temperature relationship over the final century of their 1,800-year history.

Corona *et al.* (2010) analyzed tree-ring width data obtained from 548 trees (living and dead) at 34 sites distributed across the French Alps (44°–45°30'N, 6°30'–7°45'E), which they calibrated against monthly homogenized records of temperature obtained from a network of 134 meteorological stations extending back to AD 1760, to develop a summer (June, July, August) temperature history for the period AD 751–2008 using the Regional Curve Standardization technique, which they say "has been shown to be the most appropriate age-related detrending method for

preserving multi-centennial climate variability.” This work revealed, they write, “most of the 20th century is comparable with the Medieval Warm Period,” but “during the last decade of the 20th century, the amplitude and abruptness of the summer temperature increase exceed the warming reconstructed for the Medieval Warm Period.” From their graph of the data, that exceedance appears to be about 0.4°C.

Gasiorowski and Sienkiewicz (2010) inferred the thermal conditions of Smreczynski Staw Lake (49°12'N, 19°51'E) in the Tatra Mountains of southern Poland via analyses of the distributions of various cladocera, chironomid, and diatom species they identified and quantified in a sediment core extracted from the center of the lake in the spring of 2003, which contained sediments that had accumulated there over the prior 1,500 years. This work revealed the presence of “a diverse ecosystem at the beginning of [the] record, ca. AD 360–570,” which has typically been assigned to the Dark Ages Cold Period. They found from AD 570 to 1220 “environmental conditions were better,” and various cold-water taxa were “totally absent.” The younger section of this zone—approximately its upper third (AD 850–1150), which contained the highest concentration of warm-water *Chironomus* species—“can be correlated with the Medieval Warm Period,” they write. Next came the Little Ice Age, which was the focal point of their study, extending to the start of the twentieth century, after which relative warmth once again returned, persisting to the present. Based on the *Chironomus* concentrations of the Current Warm Period, their data suggest the peak warmth of the CWP and the earlier MWP were about the same.

Sorrel *et al.* (2010) documented “the depositional history of the inner bay coeval to the mid- to late-Holocene transgression in south Brittany,” based on “an approach combining AMS ¹⁴C [radiocarbon] dating, sedimentological and rock magnetic analyses on sediment cores complemented with seismic data collected in the macrotidal Bay of Vilaine [47°20'–47°35'N, 2°50'–2°30'W].” According to the authors, “the late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives,” where they found “an increase in the contribution of riverine inputs occurred during the MWP” at “times of strong fluvial influences in the estuary during ca. 880–1050 AD.” They note, “preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal,” in

accordance with the findings of Proctor *et al.* (2000) and Meeker and Mayewski (2002). They also note the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon *et al.* (2004) and Billeaud *et al.* (2005). They write, “all sedimentary records from the French and Spanish Atlantic coasts” suggest “the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development.” In addition, “milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths,” they write.

The eight researchers state the upper successions of the sediment cores “mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals,” noting “this shift most probably documents the transition from the MWP to the Little Ice Age,” which led to the “increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and Rendell, 2009)” associated with “the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard *et al.*, 2007; Clemmensen *et al.*, 2007, 2009; Matthews and Briffa, 2005), France (Meurisse *et al.*, 2005), Netherlands (Jelgersma *et al.*, 1995) and Scotland (Dawson *et al.*, 2004).” In what they call an even “wider perspective,” they note the Medieval Warm Period “is recognized as the warmest period of the last two millennia (Mayewski *et al.*, 2004; Moberg *et al.*, 2005).”

The French scientists ultimately conclude “the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD,” suggesting “climatic conditions were probably mild enough to prevent coastal erosion in northwestern France” during this period.

Larocque-Tobler *et al.* (2010) argue “new records to increase the geographic coverage of paleoclimatic information are needed” to better describe the amplitude of temperature change during the last millennium, and “only by obtaining numerous high-resolution temperature records will it be possible to determine if the 20th century climate change

Observations: Temperature Records

exceeded the natural pre-industrial variability of European climate.” They obtained a temperature record spanning the last millennium via an analysis of fossil chironomids (non-biting midges), which they identified and quantified in four sediment cores extracted from the bed of Lake Silvaplana (46°26'56"N, 9°47'33"E) in the Upper Engadine (a high-elevation valley in the eastern Swiss Alps).

This work revealed, “at the beginning of the record, corresponding to the last part of the ‘Medieval Climate Anomaly’ (here the period between *ca.* AD 1032 and 1262), the chironomid-inferred mean July air temperatures were 1°C warmer than the climate reference period (1961–1990).” Their graphs of 20- and 50-year running means (see Figure 4.2.4.6.1.3) show the peak mean warmth of the Medieval Warm Period exceeded that of the Current Warm Period by about 0.5°C in the case of 20-year averages and 1.2°C in the case of 50-year averages. Thus the five researchers conclude, “based on the chironomid-inferred temperatures, there is no evidence mean-July air temperature exceeded the natural variability recorded during the Medieval Climate Anomaly in the 20th century at Lake Silvaplana,” noting similar results “were also obtained in northern Sweden (Grudd, 2008), in Western Europe (Guiot *et al.*, 2005), in a composite of Northern Hemisphere tree-ring reconstructions (Esper *et al.*, 2002) and a composite of tree rings and other archives (Moberg *et al.*, 2005).”

Scapozza *et al.* (2010) used radiocarbon dating of the fossil wood remains of eight larch (*Larix decidua*) stem fragments found one meter beneath the surface of the ground at the base of the front of the Piancabella rock glacier (46°27'02" N, 9°00'07" E) in the Southern Swiss Alps in September 2005, determining the wood was formed somewhere between AD 1040 and 1280 with a statistical probability of 95.4 percent. Based on this information and “geomorphological, climatological and geophysical observations,” they inferred “the treeline in the Medieval Warm Period was about 200 meters higher than in the middle of the 20th century, which corresponds to a mean summer temperature as much as 1.2°C warmer than in AD 1950.” Adjusting for warming between 1950 and the present, it can be estimated the MWP was about 0.5°C warmer than the

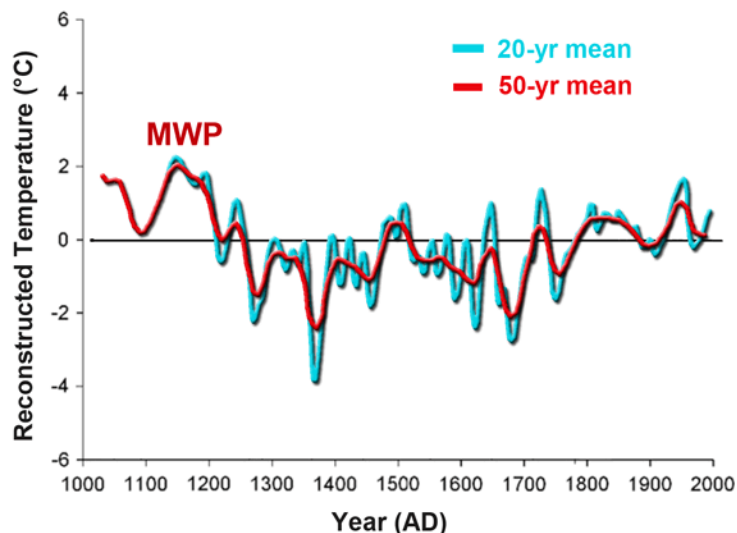


Figure 4.2.4.6.1.3. Temperature reconstruction obtained from sediment cores extracted from the bed of Lake Silvaplana in the eastern Swiss Alps. Adapted from Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M., and Kamenik, C. 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. *Quaternary Science Reviews* 29: 1940–1949.

peak warmth of the CWP.

Magny *et al.* (2011) write, “present-day global warming has provoked an increasing interest in the reconstruction of climate changes over the last millennium (Guiot *et al.*, 2005; Jones *et al.*, 2009),” which time interval is “characterized by a succession of distinct climatic phases, i.e. a Medieval Warm Period (MWP) followed by a long cooler Little Ice Age (LIA) and finally by a post-industrial rapid increase in temperature,” generally referred to as the initial phase of the Current Warm Period (CWP). In a study designed to compare the temperatures of these periods, the six scientists, working at Lake Joux (46°36'N, 6°15'E) at an altitude of 1,006 meters above sea level (a.s.l.) in the Swiss Jura Mountains, employed a multi-proxy approach with pollen and lake-level data to develop a 1,000-year history of the mean temperature of the warmest month of the year (MTWA, which was July at Lake Joux), based on the Modern Analogue Technique. They describe this procedure as “a commonly used and accepted method for the reconstruction of Lateglacial and Holocene climate oscillations from continental and marine sequences,” citing Guiot *et al.* (1993), Cheddadi *et al.*, (1997), Davis *et al.* (2003), Peyron *et al.* (2005), Kotthoff *et al.* (2008), and Pross *et al.* (2009).

Magny *et al.* report their data “give evidence of the successive climate periods generally recognized within the last 1000 years,” which they describe as “a MWP between ca. AD 1100 and 1320, (2) a LIA which, in the Joux Valley, initiated as early as ca. AD 1350 and ended at ca. AD 1870, and (3) a last warmer and drier period,” generally referred to as the beginning of the Current Warm Period (CWP).

“Considering the question of present-day global warming on a regional scale,” Magny *et al.* write, “the increase in MTWA by ca. 1.6°C observed at Laoura (1100 m a.s.l., near the Joux basin) for the period 1991–2008, when compared to the reference period 1961–1990, still appears to be in the range of the positive temperature anomaly reconstructed at Lake Joux ca. AD 1300 during the late MWP.” They note “meteorological data observed at La Brevine (1043 m a.s.l., also near the Joux basin) suggest a similar pattern with an increase in MTWA by 1°C over the period 1991–2008” relative to 1961–1990. Both of these late-twentieth/early twenty-first century temperature increases fall significantly short of that reached during the MWP, when the temperature at Joux Lake exceeded that of the 1961–1990 reference period by fully 2.0°C. The peak warmth of the MWP at Lake Joux appears to have exceeded that of the CWP at that location by 0.4–1.0°C, in harmony with similar findings obtained at other locations around the world.

Swieta-Musznicka *et al.* (2011) analyzed pollen and macrofossils taken from trench walls exposed during archaeological excavations in Gdansk (54°22'N, 18°40'E), northern Poland, as well as with similar materials contained within cores retrieved from sediments lying beneath the trenches, and discovered evidence for a population expansion of *Salvinia natans* (an aquatic fern) in the seventh or eighth century AD, which was similar to a climate-driven population expansion during the last decade. They report, “the co-occurrence of *S. natans* with other aquatic plant species was similar in both the medieval and present-day vegetation,” and “the high density of *S. natans* in the medieval population caused impoverishment of the local ecosystems in a way that has been observed in recent water bodies affected by invasive pleustophytes (free-floating plants).” Thus they conclude “the *S. natans* ‘blooms’ in the Early Middle Ages may be regarded as an extraordinary occurrence that has an analogue in the climate-driven population of this species during the last decade.”

The four researchers describe the early period of

S. natans population expansion as being due to “climate warming similar to the present time.” Elsewhere they report, “in the early medieval period, the population density of *S. natans* was similar to or higher than that observed today in shallow waters invaded by this species in the Gdansk region.” Their work suggests the medieval warmth of this part of the world was at least equal to, and perhaps warming than, the CWP.

Moschen *et al.* (2011) presented “a high resolution reconstruction of local growing season temperature anomalies at Durren Maar, Germany [50°52'N, 6°53'E], spanning the last two millennia,” which was “derived from a stable carbon isotope time series of cellulose chemically extracted from *Sphagnum* leaves ($\delta^{13}\text{C}_{\text{cellulose}}$) separated from a kettle-hole peat deposit of several meters thickness,” where the temperature reconstruction was based on the temperature dependency of *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ observed in calibration studies (Figure 4.2.4.6.1.4). The five researchers identified a cold phase with below-average temperature, lasting from the fourth to the seventh century AD, “in accordance with the so-called European Migration Period,” which has come to be known as the Dark Ages Cold Period. Thereafter, they state, “during High Medieval Times above-average temperatures are obvious.” The peak warmth of this Medieval Warm Period, which looks from the graph of their data to run from about AD 830 to AD 1150, was approximately 2.8°C greater than the peak warmth of the Current Warm Period in terms of individual anomaly points, and it was approximately 2.7°C greater in terms of 60-year running means. Between these two warm periods, the Little Ice Age could be seen to hold sway.

Expanding upon the work of some of their group two years earlier (Larocque-Tobler *et al.*, 2010), Larocque-Tobler *et al.* (2012) note “the climate of the last millennium is still controversial because too few high-resolution paleo-climate reconstructions exist to answer two key research questions”; namely, “Were the ‘Medieval Climate Anomaly’ (MCA) and the ‘Little Ice Age’ (LIA) of similar spatial extent and timing in Europe and in the Northern Hemisphere?” and “Does the amplitude of climate change of the last century exceed the natural variability?”

The second Larocque-Tobler team analyzed a lake sediment core extracted from the deepest point of Seebergsee (46°37'N, 7°28'E) in the northern Swiss Alps in AD 2005, employing chironomid head capsules preserved in the sediments to reconstruct mean July air temperatures for the past 1,000 years.

Observations: Temperature Records

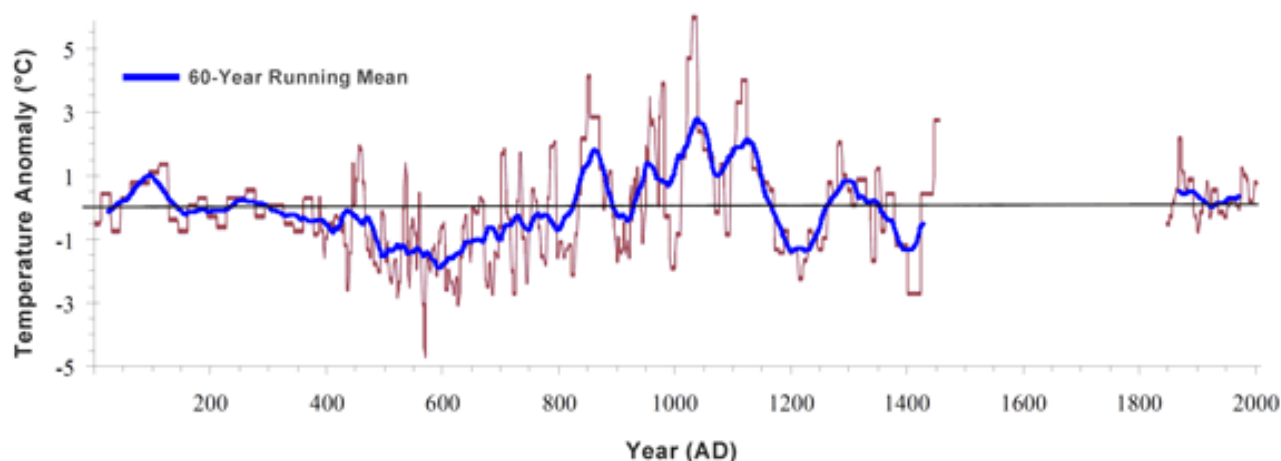


Figure 4.2.4.6.1.4. Temperature reconstruction from Dürres Maar, Germany. Adapted from Moschen, R., Kuhl, N., Peters, S., Vos, H., and Lucke, A. 2011. Temperature variability at Dürres Maar, Germany during the Migration Period and at High Medieval Times, inferred from stable carbon isotopes of *Sphagnum* cellulose. *Climate of the Past* 7: 1011–1026.

They compared their results to those of Larocque-Tobler *et al.* (2010) for another Swiss lake (Silvaplana in the eastern Alps) and to regional and European records of early instrumental data (Luterbacher *et al.*, 2004; Auer *et al.*, 2007; Böhm *et al.*, 2010), as well as a composite of paleoclimate reconstructions from the Greater Alpine Region and to millennial scale climate reconstructions of the entire Northern Hemisphere (Mangini *et al.*, 2005; Moberg *et al.*, 2005; Osborn and Briffa, 2006).

The six scientists' work revealed the peak warmth of the MCA just prior to AD 1200 was approximately 0.9°C greater than the peak warmth near the end of their record, as can be determined from the graph of their data, reproduced here as Figure 4.2.4.6.1.5. The IPCC-endorsed "hockey stick" temperature record of Mann *et al.* (1999), which gives little indication of the existence of the MCA and shows recent temperatures towering over those of that earlier time period, continues to be repudiated by real-world data. Larocque-Tobler *et al.* note their newest temperature history is "mirrored by the chironomid reconstruction from Silvaplana and the Greater Alpine Region composite of reconstructions" and "several other reconstructions from the Northern Hemisphere also show [recent] warm inferred temperatures that were not as warm as the MCA."

Niemann *et al.* (2012) point out, as so many others have, "the assessment of climate variations in Earth's history is of paramount importance for our comprehension of recent and future climate

variability." Noting "geological archives containing climate-sensitive proxy indicators are used to reconstruct paleoclimate," Niemann *et al.* employed what they describe as "a novel proxy for continental mean annual air temperature (MAAT) and soil pH" "based on the temperature (T) and pH-dependent distribution of specific bacterial membrane lipids (branched glycerol dialkyl glycerol tetraethers—GDGTs) in soil organic matter." This technique derives from the fact that "microorganisms can modify the composition of their cellular membrane lipids to adapt membrane functionality to specific environmental parameters such as T and pH," as described by Hazel and Williams (1990) and Weijers *et al.* (2007), the latter of whom devised "transfer functions that relate the degree of the GDGT methylation (expressed in the Methylation index—MBT) and cyclisation (expressed in the cyclisation ratio—CBT) to mean annual air temperature."

Niemann *et al.* used sediment cores collected in September 2009 and May 2010 from a small alpine lake (Cadagno) in the Piora Valley of south-central Switzerland, as well as soil samples taken from the surrounding catchment area. The nine Dutch and Swiss researchers report "major climate anomalies recorded by the MBT/CBT-paleothermometer" were "the Little Ice Age (~14th to 19th century) and the Medieval Warm Period (MWP, ~9th to 14th century)," which they say experienced "temperatures similar to the present-day values." They also report, "in addition to the MWP," their "lacustrine paleo T

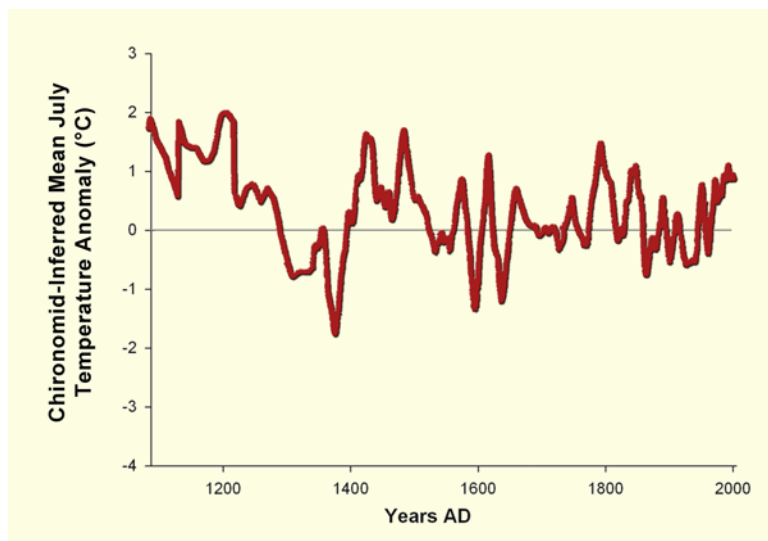


Figure 4.2.4.6.1.5. Reconstruct chironomid-inferred mean July air temperatures for the past 1,000 years, as obtained from a lake sediment core extracted from the deepest point of Seebensee (46°37'N, 7°28'E) in the northern Swiss Alps. Adapted from Larocque-Tobler, I., Stewart, M.M., Quinlan, R., Trachel, M., Kamenik, C., and Grosjean, M. 2012. A last millennium temperature reconstruction using chironomids preserved in sediments of anoxic Seebensee (Switzerland): consensus at local, regional and Central European scales. *Quaternary Science Reviews* **41**: 49–56.

record indicates Holocene warm phases at about 3, 5, 7 and 11 kyr before present, which agrees in timing with other records from both the Alps and the sub-polar North-East Atlantic Ocean.”

References

Aagaard, T., Orford, J., and Murray, A.S. 2007. Environmental controls on coastal dune formation: Skallingen Spit, Denmark. *Geomorphology* **83**: 29–47.

Auer, I., Bohm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schoner, W., Ungersbok, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Muller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., Majstorovic, M., and Nieplova, M. 2007. HISTALP: historical instrumental climatological surface time series of the Greater Alpine Region. *International Journal of Climatology* **27**: 17–46.

Bartholy, J., Pongracz, R., and Molnar, Z. 2004. Classification and analysis of past climate information based on historical documentary sources for the Carpathian Basin. *International Journal of Climatology* **24**: 1759–1776.

Billeaud, I., Chaumillon, E., and Weber, N. 2005. Evidence of a major environmental change recorded in a macrotidal bay (Marennes-Oleron Bay, France) by correlation between VHR seismic profiles and cores. *Geo-marine Letters* **25**: 1–10.

Bodri, L. and Cermak, V. 1999. Climate change of the last millennium inferred from borehole temperatures: regional patterns of climatic changes in the Czech Republic—Part III. *Global and Planetary Change* **21**: 225–235.

Bohm, R., Jones, P.D., Hiebl, J., Brunetti, M., Frank, D., and Maugeri, M. 2010. The early instrumental warm bias: a solution for long central European temperatures series 1760–2007. *Climatic Change* **101**: 41–67.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Büntgen, U., Esper, J., Frank, D.C., Nicolussi, K., and Schmidhalter, M. 2005. A 1052-year tree-ring proxy for Alpine summer temperatures. *Climate Dynamics* **25**: 141–153.

Büntgen, U., Frank, D.C., Nievergelt, D., and Esper, J. 2006. Summer temperature variations in the European Alps, A.D. 755–2004. *Journal of Climate* **19**: 5606–5623.

Chapron, E., Arnaud, F., Noel, H., Revel, M., Desmet, M., and Perdereau, L. 2005. Rhone River flood deposits in Lake Le Bourget: a proxy for Holocene environmental changes in the NW Alps, France. *Boreas* **34**: 404–416.

Chaumillon, E., Tessier, B., Weber, N., Tesson, M., and Bertin, X. 2004. Buried sandbodies within present-day estuaries (Atlantic coast of France) revealed by very high-resolution seismic surveys. *Marine Geology* **211**: 189–214.

Cheddadi, R., Yu, G., Guiot, J., Harrison, S.P., and Prentice, I.C. 1997. The climate of Europe 6000 years ago. *Climate Dynamics* **13**: 1–9.

Clarke, M.L. and Rendell, H.M. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International* **195**: 31–41.

Clemmensen, L.B., Bjornsen, M., Murray, A., and Pedersen, K. 2007. Formation of aeolian dunes on Anholt, Denmark since AD 1560: a record of deforestation and increased storminess. *Sedimentary Geology* **199**: 171–187.

Clemmensen, L.B., Murray, A., Heinemeier, J., and de Jong, R. 2009. The evolution of Holocene coastal dune

Observations: Temperature Records

- fields, Jutland, Denmark: a record of climate change over the past 5000 years. *Geomorphology* **105**: 303–313.
- Corona, C., Edouard, J.-L., Guibal, F., Guiot, J., Bernard, S., Thomas, A., and Denelle, N. 2010. Long-term summer (AD 751–2008) temperature fluctuation in the French Alps based on tree-ring data. *Boreas* **40**: 351–366.
- Davis, B.A.S., Brewer, S., Stevenson, A.C., and Guiot, J. 2003. The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews* **22**: 1701–1716.
- Dawson, S., Smith, D.E., Jordan, J., and Dawson, A.G. 2004. Late Holocene coastal sand movements in the Outer Hebrides, NW Scotland. *Marine Geology* **210**: 281–306.
- Denton, G.H. and Karlen, W. 1973. Holocene climate variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Filippi, M.L., Lambert, P., Hunziker, J., Kubler, B., and Bernasconi, S. 1999. Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millennia. *Journal of Paleolimnology* **21**: 19–34.
- Gasiorowski, M. and Sienkiewicz, E. 2010. The Little Ice Age recorded in sediments of a small dystrophic mountain lake in southern Poland. *Journal of Paleolimnology* **43**: 475–487.
- Grudd, H. 2008. Tornetrask tree-ring width and density AD 500–2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. *Climate Dynamics* **31**: 843–857.
- Guiot, J., Harrison, S.P., and Prentice, I.C. 1993. Reconstruction of Holocene pattern of moisture in Europe using pollen and lake-level data. *Quaternary Research* **40**: 139–149.
- Guiot, J., Nicault, A., Rathgeber, C., Edouard, J.L., Guibal, F., Pichard, G., and Till, C. 2005. Last-Millennium summer-temperature variations in Western Europe based on proxy data. *The Holocene* **15**: 489–500.
- Hazel, J.R. and Williams, E.E. 1990. The role of alterations in membrane lipid composition in enabling physiological adaptation of organisms to their physical environment. *Progress in Lipid Research* **29**: 167–227.
- Holzhauser, H. 1997. Fluctuations of the Grosser Aletsch Glacier and the Gorner Glacier during the last 3200 years: new results. In: Frenzel, B. (Ed.) *Glacier Fluctuations During the Holocene*. Fischer, Stuttgart, Germany, pp. 35–58.
- Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* **15**: 789–801.
- Jelgersma, S., Stive, M.J.F., and van der Walk, L. 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. *Marine Geology* **125**: 95–110.
- Joerin, U.E., Stocker, T.F., and Schluchter, C. 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene* **16**: 697–704.
- Jones, P.D., Briffa, K.R., Osborn, T.J., Lough, J.M., van Ommen, T.D., Vinther, B.M., Luterbacher, J., Wahl, E.R., Zwiers, F.W., Mann, M.E., Schmidt, G.A., Ammann, C.M., Buckley, B.M., Cobb, K.M., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Kuttel, M., Mosley-Thompson, E., Overpeck, J.T., Riedwyl, N., Schulz, M., Tudhope, A.W., Villalba, R., Wanner, H., Wolff, E., and Xoplaki, E. 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *The Holocene* **19**: 3–49.
- Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1503–1508.
- Kotthoff, U., Pross, J., Muller, U.C., Peyron, O., Schmiedle, G., Schulz, H., and Bordon, A. 2008. Climate dynamics in the borderlands of the Aegean Sea during formation of sapropel 1 deduced from a marine pollen record. *Quaternary Science Reviews* **27**: 832–845.
- Lamb, H.H. 1979. Climatic variations and changes in the wind and ocean circulation. *Quaternary Research* **11**: 1–20.
- Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M., and Kamenik, C. 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. *Quaternary Science Reviews* **29**: 1940–1949.
- Larocque-Tobler, I., Stewart, M.M., Quinlan, R., Trachsel, M., Kamenik, C., and Grosjean, M. 2012. A last millennium temperature reconstruction using chironomids preserved in sediments of anoxic Seebensee (Switzerland): consensus at local, regional and Central European scales. *Quaternary Science Reviews* **41**: 49–56.
- Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. 2004. European seasonal and annual temperature variability trends, and extremes since 1500. *Science* **303**: 1499–1503.
- Magny, M. 1993. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* **40**: 1–9.
- Magny, M., Peyron, O., Gauthier, E., Vanniere, B., Millet, L., and Vermot-Desroches, B. 2011. Quantitative estimates

Climate Change Reconsidered II

of temperature and precipitation changes over the last millennium from pollen and lake-level data at Lake Joux, Swiss Jura Mountains. *Quaternary Research* **75**: 45–54.

Mangini, A., Spotl, C., and Verdes, P. 2005. Reconstruction of temperature in the Central Alps during the past 2000 yr from a $\delta^{18}\text{O}$ stalagmite record. *Earth and Planetary Science Letters* **235**: 741–751.

Mangini, A., Verdes, P., Spotl, C., Scholz, D., Vollweiler, N., and Kromer, B. 2007. Persistent influence of the North Atlantic hydrography on central European winter temperature during the last 9000 years. *Geophysical Research Letters* **34**: 10.1029/2006GL028600.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Matthews, J.A. and Briffa, K.R. 2005. The ‘Little Ice Age’: re-evaluation of an evolving concept. *Geografiska Annaler* **87A**: 17–36.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveland, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

McDermott, F., Frisia, S., Huang, Y., Longinelli, A., Spiro, S., Heaton, T.H.E., Hawkesworth, C., Borsato, A., Keppens, E., Fairchild, I., van Borgh, C., Verheyden, S., and Selmo, E. 1999. Holocene climate variability in Europe: evidence from $\delta^{18}\text{O}$, textural and extension-rate variations in speleothems. *Quaternary Science Reviews* **18**: 1021–1038.

McDermott, F., Mathey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.

Meeker, L.D. and Mayewski, P.A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* **12**: 257–266.

Meurisse, M., van Vliet-Lanoe, B., Talon, B., and Recourt, P. 2005. Complexes dunaires et tourbeux holocenes du littoral du Nord de la France. *Comptes Rendus Geosciences* **337**: 675–684.

Millet, L., Arnaud, F., Heiri, O., Magny, M., Verneaux, V., and Desmet, M. 2009. Late-Holocene summer temperature reconstruction from chironomid assemblages of Lake Anterne, northern French Alps. *The Holocene* **19**: 317–328.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Moschen, R., Kuhl, N., Peters, S., Vos, H., and Lucke, A. 2011. Temperature variability at Durres Maar, Germany during the Migration Period and at High Medieval Times, inferred from stable carbon isotopes of *Sphagnum* cellulose. *Climate of the Past* **7**: 1011–1026.

Muller, R.A. and Gordon, J.M. 2000. *Ice Ages and Astronomical Causes*. Springer-Verlag, Berlin, Germany.

Niemann, H., Stadnitskaia, A., Wirth, S.B., Gilli, A., Anselmetti, F.S., Damste, J.S.S., Schouten, S., Hopmans, E.C., and Lehmann, M.F. 2012. Bacterial GDGTs in Holocene sediments and catchment soils of a high Alpine lake: application of the MBT/CBT-paleothermometer. *Climate of the Past* **8**: 889–906.

Niggemann, S., Mangini, A., Richter, D.K., and Wurth, G. 2003. A paleoclimate record of the last 17,600 years in stalagmites from the B7 cave, Sauerland, Germany. *Quaternary Science Reviews* **22**: 555–567.

Osborn, T.J. and Briffa, K.R. 2006. The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science* **311**: 831–834.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.

Peyron, O., Begeot, C., Brewer, S., Heiri, O., Millet, L., Ruffaldi, P., Van Campo, E., and Yu, G. 2005. Late-Glacial climatic changes in Eastern France (Lake Lautrey) from pollen, lake-levels, and chironomids. *Quaternary Research* **64**: 197–211.

Proctor, C.J., Baker, A., Barnes, W.L., and Gilmour, M.A. 2000. A thousand year speleothem record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Pross, J., Kotthoff, U., Muler, U.C., Peyron, O., Dormoy, I., Schmiedle, G., Kalaitzidis, S., and Smith, A.M. 2009. Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean region associated with the 8.2 kyr climatic event. *Geology* **37**: 887–890.

Rethly, A. 1962. *Meteorological Events and Natural Disasters in Hungary until 1700*. Academic Press, Budapest, Hungary.

Observations: Temperature Records

Rethly, A. 1970. *Meteorological Events and Natural Disasters in Hungary between 1701–1800*. Academic Press, Budapest, Hungary.

Rethly, A. and Simon, A. 1999. *Meteorological Events and Natural disasters in Hungary between 1801–1900. Vol. I-II*. Hungarian Meteorological Service, Budapest, Hungary.

Robert, C., Degiovanni, C., Jaubert, R., Leroy, V., Reyss, J.L., Saliège, J.F., Thouveny, N., and de Vernal, A. 2006. Variability of sedimentation and environment in the Berre coastal lagoon (SE France) since the first millennium: natural and anthropogenic forcings. *Journal of Geochemical Exploration* **88**: 440–444.

Scapozza, C., Lambiel, C., Reynard, E., Fallot, J.-M., Antognini, M., and Schoeneich, P. 2010. Radiocarbon dating of fossil wood remains buried by the Piancabella rock glacier, Blenio Valley (Ticino, Southern Swiss Alps): Implications for rock glacier, treeline and climate history. *Permafrost and Periglacial Processes* **21**: 90–96.

Schmidt, R., Kamenik, C., and Roth, M. 2007. Siliceous algae-based seasonal temperature inference and indicator pollen tracking ca. 4,000 years of climate/land use dependency in the southern Austrian Alps. *Journal of Paleolimnology* **38**: 541–554.

Schmidt, R., Roth, M., Tessadri, R., and Weckstrom, K. 2008. Disentangling late-Holocene climate and land use impacts on an Austrian alpine lake using seasonal temperature anomalies, ice-cover, sedimentology, and pollen tracers. *Journal of Paleolimnology* **40**: 453–469.

Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D., and Traini, C. 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): depositional history and late Holocene climatic and environmental signals. *Continental Shelf Research* **30**: 1250–1266.

Swieta-Musznicka, J., Latalowa, M., Szmaja, J., and Badura, M. 2011. *Salvinia natans* in medieval wetland deposits in Gdansk, northern Poland: evidence for the early medieval climate warming. *Journal of Paleolimnology* **45**: 369–383.

Tinner, W., Lotter, A.F., Ammann, B., Condera, M., Hubschmied, P., van Leeuwen, J.F.N., and Wehrli, M. 2003. Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to AD 800. *Quaternary Science Reviews* **22**: 1447–1460.

van Geel, B., Buurman, J., and Waterbolk, H.T. 1996. Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science* **11**: 451–460.

Vollweiler, N., Scholz, D., Muhlinghaus, C., Mangini, A.,

and Spotl, C. 2006. A precisely dated climate record for the last 9 kyr from three high alpine stalagmites, Spannagel Cave, Austria. *Geophysical Research Letters* **33**: 10.1029/2006GL027662.

Wanner, H., Dimitrios, G., Luterbacher, J., Rickli, R., Salvisberg, E., and Schmutz, C. 2000. *Klimawandel im Schweizer Alpenraum*. VDF Hochschulverlag, Zurich, Switzerland.

Weijers, J.W.H., Schouten, S., van den Donker, J.C., Hopmans, E.C., and Damste, J.S.S. 2007. Environmental controls on bacterial tetraether membrane lipid distribution in soils. *Geochimica et Cosmochimica Acta* **71**: 703–713.

4.2.4.6.2 Northern

Studying “four well-preserved continuous sediment sequences from the southern flank of the Skagerrak [58.2–58.6°N, 7.6–8.2°E],” which he described as “a current-controlled sedimentary basin between the North and Baltic Seas,” Hass (1996) carried out “granulometric and stable oxygen isotope analyses ... in order to reconstruct climate fluctuations and to evaluate climate impact during the upper Holocene.” He concludes the “Modern Climate Optimum was reached between 1940 and 1950, when temperatures exceeded the present day mean by 0.5°C.” Prior to that was the Little Ice Age, which he placed at about AD 1350–1900, and before that the Medieval Warm Period (AD 800/1000–1350), the climate of which “was characterized by warm summers, mild winters and little storm activity.” Preceding this interval was what has been called the Dark Ages Cold Period, which Hass did not name but placed between AD 400 and 700, and preceding that cold spell was the Roman Warm Period, from approximately 400 BC to AD 400. Preceding these climatic epochs was another pair of cold and warm periods.

Hass’s work adds to the evidence supporting the reality of a repetitive worldwide cycling of climate between Medieval Warm Period- and Little Ice Age-like conditions. In addition, he notes, “at the onset of the Modern Climate Optimum ... conditions change again to a level comparable to the Medieval Warm Period.

Kullman (1998) reviewed “past positional, structural and compositional shifts of tree-limits and upper boreal forests, mainly in the southern Scandes Mountains of Sweden,” based on studies of the elevational location of well-dated subfossil wood remains and the known change in air temperature with change in elevation. Among other things, he

discovered “some exceptionally warm and stable centuries, with high tree-limits and dense montane forests, occurred during the Medieval period.” He also found “an episode of warmer climate during the first half of the [twentieth] century,” but he notes tree limits and high-elevation forests at that time “were far from restored to their medieval levels,” which by AD 900–1100 “were situated 80–100 meters higher” than they were about a century ago; i.e., ~1900. He also reports “during the past few decades”—that is, during the latter part of the twentieth century—there was widespread “rapid cold-induced dieback.”

The Swedish scientist states, “the slight cooling and associated tree-limit and forest responses since the climate optimum in the late 1930s fit a more general pattern, common to the entire North Atlantic seaboard and adjacent continental areas.” He reports “there appear to have been no detectable regional or global tree-limit progression trends over the past 2–3 decades matching the GCM climate projections based on increasing CO₂ levels.” He thus concludes “since tree-limits in Scandinavia or elsewhere in the world have not reestablished at their Medieval levels, it is still possible that today’s climate, despite centennial net warming, is within its natural limits.”

Andren *et al.* (2000) conducted an extensive analysis of changes in siliceous microfossil assemblages and chemical characteristics of various materials found in a well-dated sediment core obtained from the Bornholm Basin in the southwestern Baltic Sea. The data revealed the existence of a period of high primary production at approximately AD 1050, and contemporaneous diatoms were warm water species such as *Pseudosolenia calcar-avis*, which they indicate is “a common tropical and subtropical marine planktonic species” that “cannot be found in the present Baltic Sea.” They also note what they call the Recent Baltic Sea Stage, which began about AD 1200, starts “at a point where there is a major decrease in warm water taxa in the diatom assemblage and an increase in cold water taxa, indicating a shift towards a colder climate,” which they associate with the Little Ice Age. Andren *et al.*’s data further indicate there was a period of time in the early part of the past millennium when the climate in the area of the southwestern Baltic Sea was warmer than it is today, as the sediment record of that time and vicinity contained several warm water species of diatoms, some of which can no longer be found there. This period of higher temperatures falls within “a period of early Medieval warmth dated to AD 1000–1100,” which

they note “corresponds to the time when the Vikings succeeded in colonizing Iceland and Greenland.”

Hiller *et al.* (2001) analyzed subfossil wood samples from the Khibiny mountains in the Kola Peninsula (67–68°N, 33–34°E) to reconstruct climate change there over the past 1,500 years. They determined between AD 1000 and 1300 the tree-line was located at least 100–140 m above its current elevation, an advance they describe as suggesting mean summer temperatures during this “Medieval climatic optimum” were “at least 0.8°C higher than today.” They describe this time period as hosting “the most pronounced warm climate phase on the Kola Peninsula during the last 1500 years,”

Nesje *et al.* (2001) analyzed a 572-cm-long sediment core retrieved from Norway’s Lake Atnsjoen to determine the frequency and magnitude of prehistoric floods in the southern part of that country. These efforts revealed several pronounced floods occurred throughout the 4,500-year period. The more recent portion of the record showed a time “of little flood activity around the Medieval period (AD 1000–1400),” correlated with reduced regional glacier activity, and a subsequent period of “the most extensive flood activity in the Atnsjoen catchment,” which resulted from the “post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the ‘Little Ice Age.’”

Mikalsen *et al.* (2001) conducted detailed analyses of benthic foraminifera, stable isotopes, and other sedimentary material obtained from a core extracted from a fjord in western Norway, from which they derived a relative temperature history of the region that spanned the last 5,500 years. This work revealed four cold periods characterized by 1.5–2°C reductions in bottom-water temperature—2150 to 1800 BC, 850 to 600 BC, 150 BC to AD 150, AD 500 to 600—and “a cooling that may correspond to the ‘Little Ice Age’ (AD 1625).” The three researchers also note “there is a good correlation between the cold periods and cold events recorded in other studies.” They also identified a warm period from AD 1330 to 1600 that “had the highest bottom-water temperatures in Sulafjorden during the last 5000 years.”

Brooks and Birks (2001) were deeply involved in refining protocols for using the larval-stage head capsules of midges to reconstruct temperature histories of various locations, and in this particular paper they report their progress and illustrate the application of their techniques to certain locations in Scotland and Norway. Of particular interest to the

Observations: Temperature Records

CO₂-climate debate are their findings for Lochan Uaine, in the Cairngorms region of the Scottish Highlands. This lake, they write, “is remote from human habitation and therefore any response of proxy indicators to climatic change [is] unlikely to be masked by the effects of anthropogenic environmental change in its catchment.” Reconstructed temperatures for this region peaked at about 11°C, during what they refer to as the “Little Climatic Optimum”—more typically called the Medieval Warm Period—“before cooling by about 1.5°C which may coincide with the ‘Little Ice Age.’” These results, say the two scientists, “are in good agreement with a chironomid stratigraphy from Finse, western Norway (Velle, 1998),” where summer temperatures were “about 0.4°C warmer than the present day” during the Medieval Warm Period. The latter observation also appears true for Brooks and Birks’ study, since the upper sample of the Lochane Uaine core, collected in 1993, “reconstructs the modern temperature at about 10.5°C” which is 0.5°C less than the 11°C value they obtained from the Medieval Warm Period.

McDermott *et al.* (2001) derived a $\delta^{18}\text{O}$ record from a stalagmite discovered in Crag Cave in southwestern Ireland. They compared this record with the $\delta^{18}\text{O}$ records from the GRIP and GISP2 ice cores from Greenland. They found “centennial-scale $\delta^{18}\text{O}$ variations that correlate with subtle $\delta^{18}\text{O}$ changes in the Greenland ice cores, indicating regionally coherent variability in the early Holocene.” They also report the Crag Cave data “exhibit variations that are broadly consistent with a Medieval Warm Period at $\sim 1000 \pm 200$ years ago and a two-stage Little Ice Age, as reconstructed by inverse modeling of temperature profiles in the Greenland Ice Sheet.” Also evident in the Crag Cave data were the $\delta^{18}\text{O}$ signatures of the earlier Roman Warm Period and Dark Ages Cold Period. The three researchers note the coherent $\delta^{18}\text{O}$ variations in the records from both sides of the North Atlantic “indicate that many of the subtle multicentury $\delta^{18}\text{O}$ variations in the Greenland ice cores reflect regional North Atlantic margin climate signals rather than local effects.” Their data confirm the reality of the Medieval Warm Period/Little Ice Age cycle and the prior and even-more-strongly-expressed Roman Warm Period/Dark Ages Cold Period cycle.

Voronina *et al.* (2001) analyzed dinoflagellate cyst assemblages in two sediment cores from the southeastern Barents Sea—one spanning a period of 8,300 years and one for 4,400 years—obtaining

information about sea-surface salinity, temperature, and ice cover throughout the mid- to late-Holocene. The longer of the two cores indicated a warm interval from about 8,000 to 3,000 years before present, followed by cooling pulses coincident with lowered salinity and extended ice cover in the vicinity of 5,000, 3,500, and 2,500 years ago. The shorter of the two cores also revealed cooling pulses at tentative dates of 1,400, 300, and 100 years before present. For the bulk of the past 4,400 years, ice cover lasted only two to three months per year, as opposed to the modern mean of 4.3 months per year, and August temperatures ranged between 6 and 8°C, significantly warmer than the present mean of 4.6°C. This is evidence of considerably warmer temperatures than those of today over much of the past few thousand years—including a period of time coeval with the Medieval Warm Period—in the southeastern Barents Sea, which conditions are said by Voronina *et al.* to be reflective of conditions throughout northwestern Eurasia.

Gunnarson and Linderholm (2002) worked with living and subfossil Scots pine (*Pinus sylvestris* L.) sampled close to the present tree-line in the central Scandinavian Mountains to develop a continuous 1,091-year tree-ring width chronology running from AD 909 to 1998, which they determined to be a good proxy for summer temperatures in the region. They report their data “support evidence for a ‘Medieval Warm Period,’ where growth conditions were favorable in the tenth and early eleventh centuries.” In addition, their data show the warmth of the Medieval Warm Period was both greater and longer-lasting than that of the Current Warm Period, which their data depict as having peaked around 1950.

The two Swedish scientists report their chronology “does not show the continuous temperature decrease from AD 1000 to 1900 followed by a distinct increase during the twentieth century” shown by the hockey stick temperature history of Mann *et al.* (1998, 1999). “On the contrary,” they write, their chronology “displays a positive trend from the middle of the seventeenth century, culminating around 1950, followed by strongly decreasing growth.”

Berglund (2003) identified several periods of expansion and decline of human cultures in Northwest Europe and compared them with a history of reconstructed climate “based on insolation, glacier activity, lake and sea levels, bog growth, tree line, and tree growth.” He found “a positive correlation between human impact/land-use and climate change.”

Specifically, in the latter part of the record, where both cultural and climate changes were best defined, there was, in his words, a great “retreat of agriculture” centered on about AD 500, which led to “reforestation in large areas of central Europe and Scandinavia.” He additionally notes “this period was one of rapid cooling indicated from tree-ring data (Eronen *et al.*, 1999) as well as sea surface temperatures based on diatom stratigraphy in [the] Norwegian Sea (Jansen and Koc, 2000), which can be correlated with Bond’s event 1 in North Atlantic sediments (Bond *et al.*, 1997).”

Next came what Berglund called a “boom period” that covered “several centuries from AD 700 to 1100.” This period proved to be “a favorable period for agriculture in marginal areas of Northwest Europe, leading into the so-called Medieval Warm Epoch,” when “the climate was warm and dry, with high treelines, glacier retreat, and reduced lake catchment erosion.” This period “lasted until around AD 1200, when there was a gradual change to cool/moist climate, the beginning of the Little Ice Age ... with severe consequences for the agrarian society.”

Andersson *et al.* (2003) inferred surface conditions of the eastern Norwegian Sea (Voring Plateau) from planktic stable isotopes and planktic foraminiferal assemblage concentrations in two seabed sediment cores obtained in the vicinity of 66.97°N, 7.64°W that covered the last three thousand years. The climate history derived from this study was remarkably similar to that derived by McDermott *et al.* (2001) from a high-resolution speleothem $\delta^{18}\text{O}$ record obtained from a stalagmite discovered in a cave in southwestern Ireland. At the beginning of the 3,000-year-long Voring Plateau record, for example, both regions were clearly in the end-stage of the long cold period that preceded the Roman Warm Period. Both records depicted warming from that time to the peak of the Roman Warm Period, which occurred about 2,000 years BP. Both regions then began their descent into the Dark Ages Cold Period, which lasted until the increase in temperature that produced the Medieval Warm Period, which in both records prevailed from about 800 to 550 years BP. Finally, the Little Ice Age was evident, with cold periods centered at approximately 400 and 100 years BP, again in both records.

Interestingly, neither record indicates the existence of what has come to be called the Current Warm Period. Moreover, Andersson *et al.* report, “surface ocean conditions warmer than present were common during the past 3000 years.” As time has

passed, therefore, evidence for the reality of the solar-induced millennial-scale cycling of climate described by Bond *et al.* (1997, 2001) has continued to mount, while evidence for the “unprecedented” temperature claimed for the present by the IPCC continues to be sought but not found.

Tiljander *et al.* (2003) conducted high-resolution analyses—including varve thickness, relative X-ray density, pollen and diatom assessments, and organic matter loss-on-ignition (LOI)—on a 3,000-year varved sediment sequence obtained from Lake Korttajarvi in central Finland. They compared their results with those of other palaeo-environmental studies conducted in Finland. They found “an organic rich period from AD 980 to 1250” they say “is chronologically comparable with the well-known ‘Medieval Warm Period.’” During time period, they report, “the sediment structure changes” and “less mineral material accumulates on the lake bottom than at any other time in the 3000 years sequence analyzed and the sediment is quite organic rich (LOI ~20%).” They conclude, “the winter snow cover must have been negligible, if it existed at all, and spring floods must have been of considerably lower magnitude than during the instrumental period (since AD 1881),” conditions they equate with a winter temperature approximately 2°C warmer than at present.

Tiljander *et al.* cite much corroborative evidence in support of this conclusion. They note, for example, “the relative lack of mineral matter accumulation and high proportion of organic material between AD 950 and 1200 was also noticed in two varved lakes in eastern Finland (Saarinen *et al.*, 2001) as well as in varves of Lake Nautajarvi in central Finland c. AD 1000–1200 (Ojala, 2001).” They also note “a study based on oak barrels, which were used to pay taxes in AD 1250–1300, indicates oak forests grew 150 km north of their present distribution in SW Finland and this latitudinal extension implies a summer temperature 1–2°C higher than today (Hulden, 2001).” And they report “a pollen reconstruction from northern Finland suggests that the July mean temperature was c. 0.8°C warmer than today during the Medieval Climate Anomaly (Seppa, 2001).” In these studies, therefore, the scientists conclude both summer and winter temperatures over much of the Medieval Warm Period throughout many parts of Finland were significantly warmer than they are at present.

Roncaglia (2004) analyzed variations in organic matter deposition from approximately 6,350 cal yr BC to AD 1430 in a sediment core extracted from the

Observations: Temperature Records

Skalafjord, southern Eysturoy, Faroe Islands to assess climatic conditions in that part of the North Atlantic from the mid- to late-Holocene. She reports an increase in “structured brown phytoclasts, plant tissue and sporomorphs in the sediments dating to ca. AD 830–1090 indicate increased terrestrial influx and inland vegetation supporting the idea of improved climatic conditions,” while also noting “the increase in the amount of structured brown phytoclasts, leaf and membranous tissue and sporomorphs indicated increased inland vegetation probably related to improved climatic conditions and/or the presence of cultivated crops on the islands.” In addition, she found high “total dinoflagellate cyst concentration and increased absolute amount of loricae of tintinnid and planktonic crustacean eggs occurred at ca. AD 830–1090,” concluding these observations “may suggest increased primary productivity in the waters of the fjord,” citing Lewis *et al.* (1990) and Sangiorgi *et al.* (2002).

Roncaglia writes, the “amelioration of climate conditions,” which promoted the enhanced productivity of both land and sea at this time, “may encompass the Medieval Warm Period in the Faroe region.” She also reports an increased concentration of certain other organisms at about AD 1090–1260, which she says “suggests a cooling, which may reflect the beginning of the Little Ice Age.” Thus evidence for both the Medieval Warm Period and Little Ice Age is clear in the sediments of a Faroe Island fjord, demonstrating that even at sea, these major recurring extremes of cyclical Holocene climate make their presence felt to such a degree that they significantly influence both aquatic and terrestrial primary production.

Hormes *et al.* (2004) identified and dated periods of soil formation in moraines in the Kebnekaise mountain region of Swedish Lapland in the foreground of the Nipalsglaciaren (67°58'N, 18°33'E) and compared the climatic implications of their results with those of other proxy climate records derived in other areas of northern and central Scandinavia. Two main periods of soil formation were identified (2750–2000 and 1170–740 cal yr BP), and these time spans coincide nearly perfectly with the Roman and Medieval Warm Periods delineated by McDermott *et al.* (2001) in the high-resolution $\delta^{18}\text{O}$ record they developed from a stalagmite in southwestern Ireland's Crag Cave.

Hormes *et al.* also report the periods during which the soil formation processes took place “represent periods where the Nipalsglacier did not

reach the position of the moraine,” and “the glacier was most likely in a position similar to today, and climate conditions were also similar to today.” Comparing their findings with those of other investigators, they report the following with respect to the Medieval Warm Period:

(1) Pollen profiles derived from sediments of Lake Tibetanus in Lapland (Hammarlund *et al.*, 2002) “infer increased mean July temperatures ... peaking around 1000 cal yr BP.”

(2) Oxygen isotope studies in nearby Lake 850 “record changes around 1000 cal yr BP towards favorable climate conditions (Shemesh *et al.*, 2001).”

(3) At Lake Laihalampi in southern Finland, “pollen-based reconstructions of mean temperatures indicate 0.5°C higher values between 1200 and 1100 cal yr BP (Heikkila and Seppa, 2003).”

(4) Radiocarbon ages of mosses in front of Arjep Ruotesjekna in the Sarek Mountains of Swedish Lapland “support the conclusion that between 1170 and 920 cal yr BP the glaciers had not reached the 1970s limit (Karlen and Denton, 1975).”

(5) Reconstructed temperatures of a pine dendrochronology from northern Fennoscandia “show temperatures between 1100 and 750 cal yr BP to have been around 0.8°C higher than today (Grudd *et al.*, 2002).”

(6, 7) At Haugabreen glacier (Matthews, 1980) and Storbreen glacier (Griffey and Matthews, 1978) in southern maritime Norway, “soil formation on moraines was dated between 1060 and 790 cal yr BP.”

(8) Alder trees were melted out from Engabreen glacier (Worsley and Alexander, 1976), “suggesting a smaller extension of this Norwegian glacier between 1180 and 790 cal yr BP supporting warm/dry conditions during that time in central Norway.”

(9) Jostedalsbreen glacier “receded between 1000 and 900 cal yr BP (Nesje *et al.*, 2001).”

With respect to their identification of the Roman Warm Period, Hormes *et al.* report prior findings of soil formation at (1) Svartisen glacier between 2,350 and 1,990 cal yr BP by Karlen (1979), (2) Austre Okstindbreen glacier between 2,350 and 1,800 cal yr BP by Griffey and Worsley (1978), and (3) Austre Okstindbreen glacier between 2,750 and 2,150 by Karlen (1979). In addition, they note:

(4) The pine tree-based temperature history of northern Fennoscandia developed by Grudd *et al.* (2002) “discloses a spike +2°C higher than today's around 2300 cal yr BP.”

(5, 6, 7, 8, 9) “The lacustrine records in Lapland

and Finland are also consistent with supposition of a warmer climate than at present before 2000 cal yr BP and cooler temperatures before 2450 cal yr BP (Rosen *et al.*, 2001; Seppa and Birks, 2001; Shemesh *et al.*, 2001; Hammarlund *et al.*, 2002; Heikkila and Seppa, 2003)."

In view of these many research findings, it is clear both the Medieval and Roman Warm Periods were very real features of Scandinavian climatic history, and they were likely even warmer than the Current Warm Period has been to date.

Blundell and Barber (2005) used plant macrofossils, testate amoebae, and degree of humification as proxies for environmental moisture conditions to develop a 2,800-year "wetness history" from a peat core extracted from Tore Hill Moss, a raised bog in the Strathspey region of Scotland. Based on the results they obtained from the three proxies they studied, they derived a relative wetness history that began 2,800 years ago and extended to AD 2000.

The most clearly defined and longest interval of sustained dryness of this history stretched from about AD 850 to AD 1080, coincident with the well-known Medieval Warm Period, while the most extreme wetness interval occurred during the depths of the last stage of the Little Ice Age. Also evident in the two scientists' wetness history was a period of relative dryness centered on about AD 1550, which corresponded to a period of relative warmth that has previously been documented by several other studies. Preceding the Medieval Warm Period, their hydro-climate reconstruction reveals a highly chaotic period of generally greater wetness that corresponds to the Dark Ages Cold Period, while also evident were dryness peaks representing the Roman Warm Period and two other periods of relative dryness located about 500 years on either side of its center.

The correlation this study demonstrates to exist between relative wetness and warmth in Scotland strongly suggests the temperature of the late twentieth century was nowhere near the highest of the past two millennia in that part of the world, as five other periods over the past 2,800 years were considerably warmer. Blundell and Barber cite many studies that report findings similar to theirs throughout much of the rest of Europe and the North Atlantic Ocean.

Linderholm and Gunnarson (2005) developed what they called the Jämtland multi-millennial tree-ring width chronology, derived from living and subfossil Scots pines (*Pinus sylvestris* L.) sampled close to the present tree-line in the central Scandinavian Mountains. This record spanned 2893

BC to AD 2002, with minor gaps at 1633–1650 BC and AD 887–907. The two researchers focused their analysis on the well-replicated period of 1632 BC to AD 2000, utilizing it as a proxy for summer temperatures.

Several periods of anomalously warm and cold summers were noted throughout the record: 550 to 450 BC (Roman Warm Period), when summer temperatures were the warmest of the entire record, exceeding the 1961–1990 mean by more than 6°C; AD 300 to 400 (Dark Ages Cold Period), which was "the longest period of consecutive cold summers," averaging 1.5°C less than the 1961–1990 mean; AD 900 to 1000, a warm era corresponding to the Medieval Warm Period; and AD 1550 to 1900, a cold period known as the Little Ice Age. With respect to the final section of the tree-ring record, which encompasses the period of modern warming, Linderholm and Gunnarson state this phenomenon "does not stand out as an anomalous feature in the 3600-year record," noting "other periods show more rapid warming and also higher summer temperatures."

Berge *et al.* (2005) describe and discuss the significance of what they refer to as "the first observations of settled blue mussels *Mytilus edulis* L. in the high Arctic Archipelago of Svalbard for the first time since the Viking Age." This discovery of the blue mussel colony was made by divers in August and September 2004 at Sagaskjaeret, Isfjorden, Svalbard (78°13'N, 14°E). Subsequent inferences of the five researchers with regard to pertinent regional climatic and oceanographic conditions over the prior few years led them to conclude "the majority of blue mussels were transported as larvae in unusually warm water by the West Spitsbergen Current from the mainland of Norway to Spitsbergen during the summer of 2002." They write "it is highly probable that the newly established blue mussel population is a direct response to a recent increase in sea surface temperatures."

Berge *et al.* further note the "distribution patterns of blue mussels *Mytilus edulis* L. in the high Arctic indicate that this thermophilous mollusk was abundant along the west coast of Svalbard during warm intervals (Salvigsen *et al.*, 1992; Salvigsen, 2002) in the Holocene," but mussels of this species "have not been present at Svalbard for the last 1000 years (Salvigsen, 2002)." In light of these well-documented real-world observations, including the fact that blue mussels only recently had begun to reestablish themselves in this part of the world, they

Observations: Temperature Records

conclude water temperatures there were only beginning to “approach those of the mediaeval warm period.”

Weckstrom *et al.* (2006) developed a high-resolution quantitative history of temperature variability over the past 800 years, based on analyses of diatoms found in a sediment core retrieved from a treeline lake—Lake Tsuolbmajavri (68°41'N, 22°05'E)—in Finnish Lapland. The work revealed the “termination phase of the MWP,” which they indicate as having occurred between AD 1200 and 1300, was 0.15°C warmer than the peak warmth of the Current Warm Period, which in their history occurred at the conclusion of the twentieth century (see Figure 4.2.4.6.2.1).

Eiriksson *et al.* (2006) reconstructed the near-shore thermal history of the North Atlantic Current along the western coast of Europe over the last two millennia, based on measurements of stable isotopes, benthic and planktonic foraminifera, diatoms, and dinoflagellates, as well as geochemical and sedimentological parameters, which they acquired on the Iberian margin, the West Scotland margin, the Norwegian margin, and the North Icelandic shelf. In addition to identifying the Roman Warm Period (nominally 50 BC–AD 400), which exhibited the warmest sea surface temperatures of the last two millennia on both the Iberian margin and the North Icelandic shelf, and the following Dark Ages Cold Period (AD 400–800), Eiriksson *et al.* report detecting the Medieval Warm Period (AD 800–1300) and Little Ice Age (AD 1300–1900), which was followed in some records by a strong warming to the present. They stated the latter warming “does not appear to be unusual when the proxy records spanning the last two millennia are examined.”

The results of Eiriksson *et al.*'s research confirm the millennial-scale climatic oscillation that has been responsible for periodically producing centennial-scale warm and cold periods throughout Earth's history. It also reveals there is nothing unusual or unnatural about the Current Warm Period, which in the case of two of their four sites was found to be somewhat cooler than it was during the Roman Warm

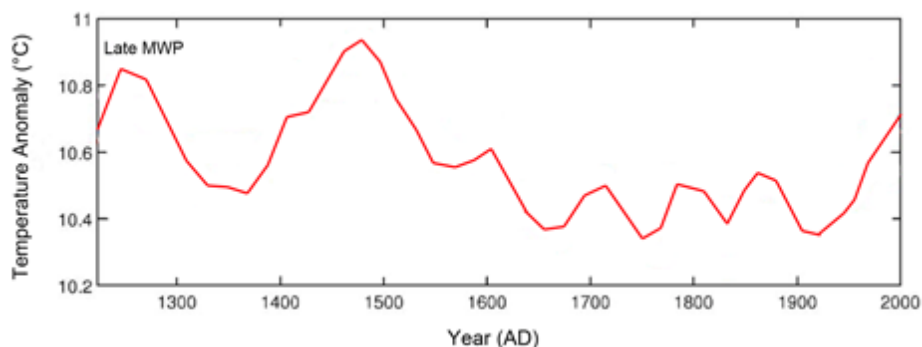


Figure 4.2.4.6.2.1. Decadally smoothed diatom-based temperature reconstruction from Lake Tsuolbmajavri in Finnish Lapland. Adapted from Weckstrom, J., Korhola, A., Erasto, P., and Holmstrom, L. 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. *Quaternary Research* 66: 78–86.

Period of 2,000 years ago, when the atmosphere's CO₂ concentration was more than 100 ppm less than it is today.

Haltia-Hovi *et al.* (2007) extracted sediment cores from beneath the 0.7-m-thick ice platform on Lake Lehmilampi (63°37'N, 29°06'E) in North Karelia, eastern Finland, in the springs of 2004 and 2005. They identified and counted the approximately 2,000 annual varves contained in the cores and measured their individual thicknesses and mineral and organic matter contents. They compared these climate-related data with residual $\Delta^{14}\text{C}$ data derived from tree rings, which serve as a proxy for solar activity. They report their “comparison of varve parameters (varve thickness, mineral and organic matter accumulation) and the activity of the sun, as reflected in residual $\Delta^{14}\text{C}$ [data] appears to coincide remarkably well in Lake Lehmilampi during the last 2000 years, suggesting solar forcing of the climate.”

In addition, the Finnish researchers state, “the low deposition rate of mineral matter in AD 1060–1280 possibly implies mild winters with a short ice cover period during that time with minor snow accumulation interrupted by thawing periods.” They note the low accumulation of organic matter during this period “suggests a long open water season and a high decomposition rate of organic matter.” Consequently, since the AD 1060–1280 period shows by far the lowest levels of both mineral and organic matter content (Figure 4.2.4.6.2.2), and since “the thinnest varves of the last 2000 years were deposited during [the] solar activity maxima in the Middle Ages,” it is difficult not to conclude the period was likely the warmest of the past two millennia.

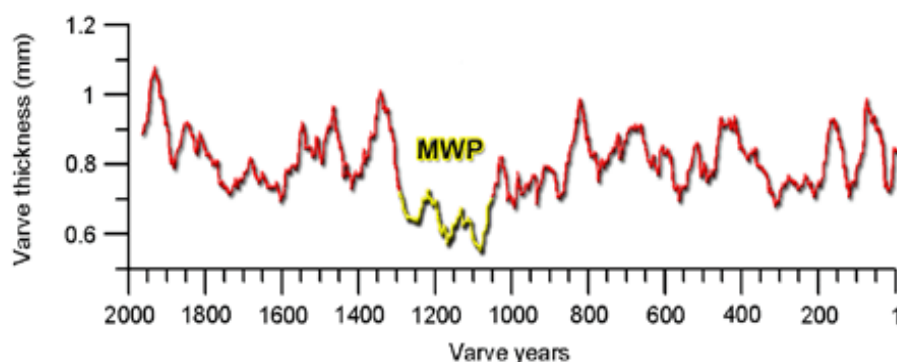


Figure 4.2.4.6.2.2. Varve thickness from sediment cores obtained from Lake Lehmilampi, eastern Finland. Adapted from Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* 26: 678–689.

Allen *et al.* (2007) analyzed pollen characteristics within sediment cores retrieved from a small unnamed lake located at 71°02'18"N, 28°10'6.6"E near the coast of Nordkinnhalvoya, Finnmark, Norway and constructed a climatic history of the area. They found "regional vegetation responded to Holocene climatic variability at centennial-millennial time scales" and report, "the most recent widely documented cooling event, the Little Ice Age of ca 450–100 cal BP, also is reflected in our data by a minimum in *Pinus:Betula* [pollen] ratio beginning ca 300 cal BP and ending only in the recent past." They also note, "the Dark Ages cool interval, a period during which various other proxies indicate cooling in Fennoscandia and beyond, is evident too, corresponding to lower values of *Pinus:Betula* [pollen] ratio ca 1600–1100 cal BP." In addition, "the Medieval Warm Period that separated the latter two cool intervals also is strongly reflected in our data, as is the warm period around two millennia ago during which the Roman Empire reached its peak."

Jiang *et al.* (2007) analyzed diatom data they obtained from core MD992271 (66°30'05"N, 19°30'20"W) on the North Icelandic shelf to derive summer sea surface temperatures (SSTs) for that location based on relative abundances of warm and cold water species. They compared the results they obtained with results derived by Jiang *et al.* (2002, 2005) via similar analyses of nearby cores HM107-03 (66°30'N, 19°04'W) and MD992275 (66°33'N, 17°42'W), as well as results derived from GISP2 $\delta^{18}\text{O}$ data and other marine sediment records obtained from other regions of the North Atlantic.

The data from the new sediment core revealed a gradually decreasing temperature trend over the entire

reconstructed 3,000-year SST record, with superimposed centennial- and millennial-scale summer SST fluctuations. In addition, Jiang *et al.* write, "the Medieval Warm Period and the Little Ice Age are identified in the record," with the former period appearing to have prevailed between approximately AD 950 and 1250. The MD992271 record ended in the midst of the Little Ice Age and therefore did not reveal any nineteenth or twentieth century warming.

The HM107-03 record, on the other hand, extended to within about 50 years of the present, but it too showed no evidence of any warming at its end. Core MD992275 extended to the nominal present, however, and it suggested the end of the twentieth century was at least three-quarters of a degree Centigrade cooler than the peak temperature of the Medieval Warm Period, about the same qualitative and quantitative difference suggested by the GISP2 $\delta^{18}\text{O}$ data.

Jiang *et al.* note, "comparison of the data from core MD992271 with those from two other cores, HM107-03 and MD992275, on the North Icelandic shelf shows coherent late Holocene changes in reconstructed summer SST values ... reflecting regional changes in the summer SSTs on the North Icelandic shelf." They conclude, "the consistency between changes in the late Holocene summer SSTs on the North Icelandic shelf and in GISP2 $\delta^{18}\text{O}$ data, as well as in other marine sediment records from the North Atlantic, further suggests synchronous North Atlantic-wide climate fluctuations."

Justwan *et al.* (2008) reconstructed August sea surface temperatures with a resolution of 40 years over the past 11,000-plus years based on analyses of diatoms found in a sediment core extracted from the northern Icelandic shelf (66°37'53"N, 20°51'16"W). Figure 4.2.4.6.2.3 illustrates the data for the most recent two millennia of this record, showing the peak warmth of the MWP is essentially identical to the peak warmth of the Current Warm Period, albeit the peak warmth of the CWP does not appear at its current endpoint, which would technically make the CWP's current temperature about 0.5°C less than the

Observations: Temperature Records

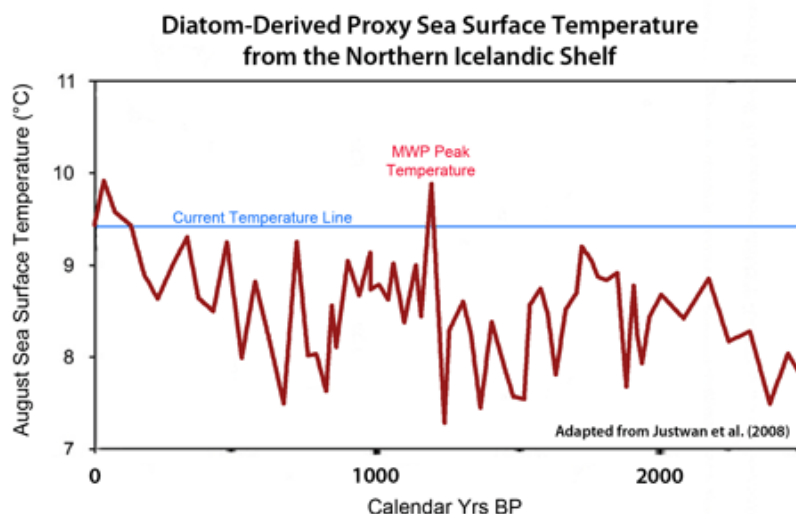


Figure 4.2.4.6.2.3. A diatom-based sea surface temperature reconstruction from the northern Icelandic shelf. Adapted from Justwan, A., Koc, N., and Jennings, A.E. 2008. Evolution of the Irminger and East Icelandic Current systems through the Holocene, revealed by diatom-based sea surface temperature reconstructions. *Quaternary Science Reviews* 27: 1571–1582.

peak MWP temperature.

Leipe *et al.* (2008) analyzed five 60-cm sediment cores retrieved from the eastern Gotland Basin in the central Baltic Sea (~56°55'–57°15'N, 19°20'–20°00'E) for a variety of physical, chemical, and biological properties. They report, “during the Medieval Warm Period, from about AD 900 to 1250, the hydrographic and environmental conditions were similar to those of the present time.” They note, moreover, analyses of lignin compounds in the sediment cores, which “can be used to characterize terrigenous organic matter from plants,” pointed to the Medieval Warm Period possibly being warmer than the Current Warm Period.

Sicre *et al.* (2008) developed a unique, 2,000-year-long summer sea surface temperature (SST) record with unprecedented temporal resolution (2–5 years) from a sediment core retrieved off North Iceland (66°33'N, 17°42'W), based on their analyses of alkenones synthesized primarily in the summer by the marine alga *Emiliania huxleyi* that grew in the overlying ocean's surface waters, dating the SST data by tephrochronology. Figure 4.2.4.6.2.4 is adapted from the temperature history they derived. Of particular interest is its clear depiction of the millennial-scale oscillation of climate that produced the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period.

In comparing prior temperatures to those of the near-present, the figure shows the SST record peaks at about 8.3°C somewhere around 1940, a particularly warm time in Earth's modern history. However, the researchers show a “modern temperature” of 9°C they determined from a box-core of nearby surface sediment, which they say “is consistent with the recent compilation produced by Hanna *et al.* (2006).” The latter reported, “since 1874, July and August SSTs measured at Grimsey Island have varied between 6.7 and 9°C,” which suggests Sicre *et al.*'s 9°C value is the *peak* modern temperature observed in the time of Hanna *et al.*'s analysis. It can be concluded the peak temperature of the Medieval Warm Period was fully 1°C warmer than the peak temperature of the Current Warm Period, and the peak temperature of the Roman Warm

Period was about 0.5°C warmer than that of the Current Warm Period.

Grudd (2008) notes many tree-ring-based temperature histories terminate far short of the end of the twentieth century, and he states there is thus “an urgent need to update existing tree-ring collections throughout the northern hemisphere,” especially to make valid comparisons of past high-temperature periods, such as the Medieval Warm Period, with the present.

Working with an extensive set of Scots pine (*Pinus sylvestris* L.) tree-ring maximum density (MXD) data from the Torneträsk area of northern Sweden, originally compiled by Schweingruber *et al.* (1988) and covering the period AD 441–1980, Grudd extended the record an additional 24 years to 2004 using new samples obtained from 35 relatively young trees. This had the effect of reducing the mean cambial age of the MXD data in the twentieth century and thus eliminating a disturbing “loss of sensitivity to temperature, apparent in earlier versions of the Torneträsk MXD chronology (Briffa, 2000).” The results are depicted in Figure 4.2.4.6.2.5.

Grudd concluded, as is readily evident from the results presented in the figure above, “the late-twentieth century is not exceptionally warm in the new Torneträsk record,” since “on decadal-to-century timescales, periods around AD 750, 1000, 1400 and 1750 were all equally warm, or warmer.” He states,

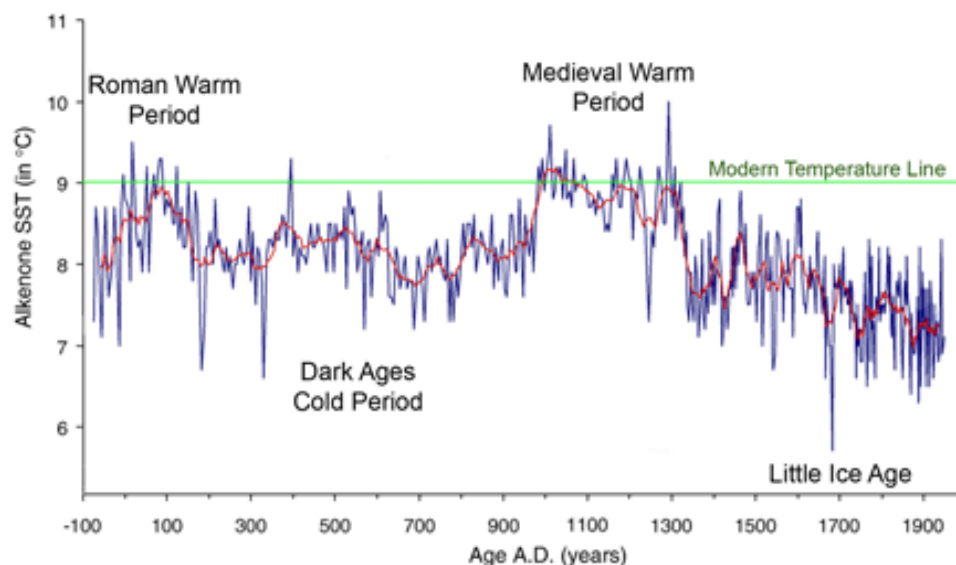


Figure 4.2.4.6.2.4. A 2,000-year summer sea surface temperature record derived from an ocean sediment core off the coast of north Iceland. Adapted from Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L., Jansen, E., and Turon, J.-L. 2008. Decadal variability of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary Science Letters* **268**: 137–142.

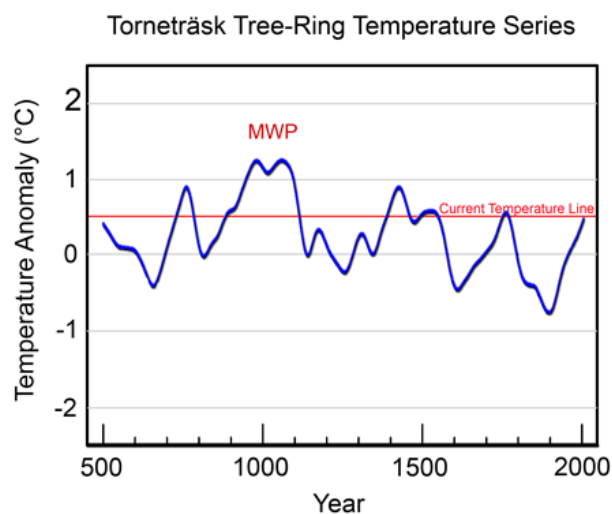


Figure 4.2.4.6.2.5. Tree-ring temperature proxy from Torneträsk, Sweden. Adapted from Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L., Jansen, E., and Turon, J.-L. 2008. Decadal variability of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary Science Letters* **268**: 137–142.

“the warmest summers in this new reconstruction occur in a 200-year period centered on AD 1000,”

leading him to declare, “Fennoscandia seems to have been significantly warmer during medieval times as compared to the late-twentieth century,” and this period “was much warmer than previously recognized.” In addition, he notes, “a warm period around AD 1000 is in line with evidence from other proxy indicators from northern Fennoscandia,” writing, “pine tree-limit (Shemesh *et al.*, 2001; Helama *et al.*, 2004; Kultti *et al.*, 2006) [and] pollen and diatoms (Korhola *et al.*, 2000; Seppa and Birks, 2002; Bigler *et al.*, 2006) show indisputable evidence of a ‘Medieval Warm Period’ that was warmer than the twentieth century climate.”

Helama *et al.* (2009) used data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland and regional curve standardization (RCS) procedures to develop what they describe as “the first European dendroclimatic precipitation reconstruction,” which “covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP),” running from AD 670 to AD 1993. These data, they write, indicate “the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD,” which “precisely overlaps the period commonly referred to

Observations: Temperature Records

as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture.” In addition, they report “the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930).”

The three Finnish scientists note “the global medieval drought that we found occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook *et al.*, 2004, 2007), eastern South America (Stine, 1994; Rein *et al.*, 2004), and equatorial East Africa (Verschuren *et al.*, 2000; Russell and Johnson, 2005, 2007; Stager *et al.*, 2005) between AD 900 and 1300.” Noting further “the global evidence argues for a common force behind the hydrological component of the MCA,” they report “previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren *et al.*, 2000; Stager *et al.*, 2005) or the ENSO (Cook *et al.*, 2004, 2007; Rein *et al.*, 2004; Herweijer *et al.*, 2006, 2007; Graham *et al.*, 2007; Seager *et al.*, 2007).” They conclude, “the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the $\Delta^{14}\text{C}$ and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki *et al.*, 2004).”

Bjune *et al.* (2009) used mean July temperature reconstructions based on “pollen-stratigraphical data obtained from eleven small lakes located in the middle boreal, northern boreal, low-alpine, or low-arctic zones of northern Norway, northern Sweden, northern Finland and north-west Russia” to develop a mean quantitative temperature history spanning the past two millennia for this Northern Fennoscandia region (66°25′–70°50′N, 14°03′–35°19′E). They report, “no consistent temperature peak is observed during the ‘Medieval Warm Period.’” But a graph of their final result (see Figure 4.2.4.6.2.6) shows what they describe as the present temperature (red vertical line)—derived from the uppermost 1 cm of the sediment cores, which were collected at various times between AD 1994 and 2003—is colder than almost all of the data points obtained by the authors over the past 2,000 years. Focusing on the Medieval Warm Period, it is evident temperatures then were as much as 1.4°C warmer than what they were over the most recent decade or so.

Axford *et al.* (2009) write, “the idea of a widespread and spatially coherent ‘Medieval Warm

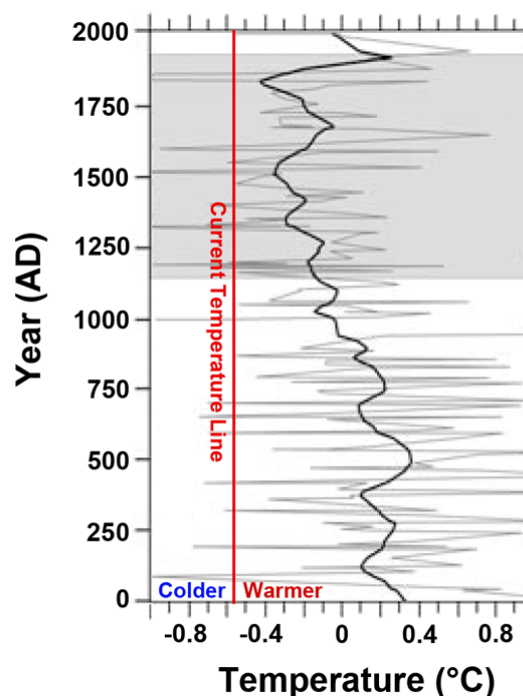


Figure 4.2.4.6.2.6. Mean July temperature reconstruction based on pollen-stratigraphical data obtained from eleven small lakes located in the boreal and alpine low-arctic zones of northern Norway, northern Sweden, northern Finland and north-west Russia. Adapted from Bjune, A.E., Seppä, H., and Birks, H.J.B. 2009. Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *Journal of Paleolimnology* 41: 43–56.

Period’ (MWP) has come under scrutiny in recent years,” but “it remains a viable hypothesis that a period of relative warmth in northwestern Europe and the northern North Atlantic region helped facilitate Norse expansion across the North Atlantic from the ninth to thirteenth centuries, including settlement of Iceland and Greenland,” and “subsequent cooling contributed to the demise of the Norse settlements on Greenland.” They developed a regional climatic record from a sediment core retrieved from lake Stora Vioarvatn in northeast Iceland (66°14.232′N, 15°50.083′W) in the summer of 2005, based on chironomid assemblage data, which were well correlated with nearby measured temperatures over the 170-year instrumental record, and total organic carbon, nitrogen, and biogenic silica content.

The four researchers report their data indicated “warm temperatures in the tenth and eleventh centuries, with one data point suggesting temperatures slightly warmer than present.” They also found

“temperatures were higher overall and more consistently high through much of the first millennium AD” (see Figure 4.2.4.6.2.7).

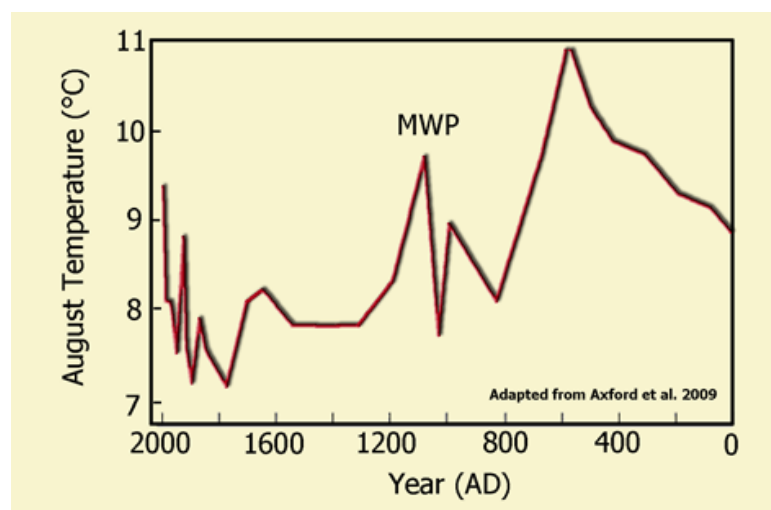


Figure 4.2.4.6.2.7. August temperature reconstruction from Lake Stora Vioarvatn. Adapted from Axford, Y., Geirsdottir, A., Miller, G.H., and Langdon, P.G. 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. *Journal of Paleolimnology* 41: 7–24.

The Icelandic, UK and U.S. scientists write, “the historical perception of a significant medieval climate anomaly in Iceland may be primarily a reflection of the human perspective,” in that “Iceland was settled ca. AD 870, during a period of relative warmth that was followed by many centuries of progressively colder and less hospitable climate.” They also note, “had the Norse settled Iceland 1000 years earlier, the MWP might be viewed only as a brief period of climatic amelioration, a respite from a shift to colder temperatures that began in the eighth century,” near the end of several centuries of even greater warmth. Viewed from either perspective, it is clear there is nothing unusual or unnatural about the region’s present-day temperatures, which the researchers say “do not show much recent warming.”

Stancikaite *et al.* (2009) carried out interdisciplinary research at the Impiltis hill fort and settlement area of Northwest Lithuania “to study the climate and the human impact on the landscape, the development of the settlement and the hill fort, the types of agriculture employed there, and changes in the local economy.” They determined “the transition from the first to the second millennium AD, also the onset of the ‘Medieval Warm Period,’ coincided with

a period of intensive human activity at the Impiltis hill fort and settlement area.”

There was at that time, they discovered, “a high intensity of farming activities, which were supported by favorable climatic conditions and included the existence of permanent agricultural fields as well as the earliest record of rye cultivation in NW Lithuania.” The “period of most prominent human activity in the Impiltis,” as the eight researchers describe it, “was dated back to about 1050–1250 AD,” when they suggest “the favorable climatic conditions of [this] ‘Medieval Warm Period’ may have supported human activity during its maximum phase.” This inference, they write, “correlates well with the chronology of the hill fort and settlement prosperity as represented in data collected from the site.” Thereafter, they further suggest, “it is possible that the ensuing gradual regression of human activity was caused, in part, by the climatic deterioration known as the ‘Little Ice Age.’”

Bonnet *et al.* (2010) developed a high-resolution record of ocean and climate variations during the late Holocene in the Fram Strait (the major gateway between the Arctic and North Atlantic Oceans, located north of the Greenland Sea), using detailed analyses of a sediment core recovered from a location (78°54.931’N, 6°46.005’E) on the slope of the western continental margin of Svalbard, based on analyses of organic-walled dinoflagellate cysts that permit the reconstruction of sea-surface conditions in both summer and winter. The latter reconstructions, they write, “were made using two different approaches for comparison and to insure the robustness of estimates.” These were “the modern analogue technique, which is based on the similarity degree between fossil and modern spectra” and “the artificial neural network technique, which relies on calibration between hydrographical parameters and assemblages.”

Bonnet *et al.* discovered the sea surface temperature (SST) histories they developed were “nearly identical and show oscillations between -1°C and 5.5°C in winter and between 2.4°C and 10.0°C in summer.” Their graphical results show between 2,500 and 250 years before present (BP), the mean SSTs of summers were warmer than those of the present about 80 percent of the time, and the mean SSTs of winters

Observations: Temperature Records

exceeded those of current winters approximately 75 percent of the time, with the long-term (2,250-year) means of both seasonal periods averaging about 2°C more than current means. In addition, the highest temperatures were recorded around 1,320 cal. years BP, during a warm interval that persisted from about AD 500 to 720 during the very earliest stages of the Medieval Warm Period (MWP), when the peak summer and winter temperatures exceeded the peak summer and winter temperatures of the first several years of the twenty-first century by about 3°C.

Haltia-Hovi *et al.* (2010) write, “lacustrine sediment magnetic assemblages respond sensitively to environmental changes,” and “characteristics of magnetic minerals, i.e. their concentration, mineralogy and grain size in sediments, can be studied by making mineral magnetic measurements, which yield large quantities of environmental data rapidly and non-destructively,” citing Evans and Heller (2003). Working with two sediment cores taken from Finland’s Lake Lehmilampi (63°37’N, 29°06’E), they constructed detailed chronological histories of several magnetic properties of the sediments, as well as a history of their total organic carbon content.

The four researchers discovered a “conspicuous occurrence of fine magnetic particles and high organic concentration” evident around 4,700–4,300 Cal. yrs BP. This period, they note, “is broadly coincident with glacier contraction and treelines higher than present in the Scandinavian mountains according to Denton and Karlen (1973) and Karlen and Kuylensstierna (1996).” From that time on toward the present, there was a “decreasing trend of magnetic concentration, except for the slight localized enhancement in the upper part of the sediment column at ~1,100–900 Cal. yrs BP,” where the year zero BP = AD 1950.

Changes of these types have been attributed in prior studies to magnetotactic bacteria (e.g. *Magneto-spirillum* spp.), which Haltia-Hovi *et al.* describe as “aquatic organisms that produce internal, small magnetite or greigite grains” that are used “to navigate along the geomagnetic field lines in search of micro or anaerobic conditions in the lake bottom,” as described by Blakemore (1982) and Bazylinski and Williams (2007). They further note the studies of Snowball (1994), Kim *et al.* (2005), and Paasche *et al.* (2004) “showed magnetic concentration enhancement, pointing to greater metabolic activity of these aquatic organisms in the presence of abundant organic matter,” which is also what Haltia-Hovi *et al.*

The latter scientists report the “concentration of organic matter in the sediment is highest, together with fine magnetic grain sizes, in the time period 1,100–900 Cal. years BP,” and they say this time interval “is associated with warmer temperatures during the Medieval Climate Anomaly according to the varve parameters of Lake Lehmilampi,” citing the precise core-dating by varve-counting work of Haltia-Hovi *et al.* (2007). Taken together, these observations strongly suggest the peak warmth of the Medieval Warm Period (about AD 850–1050) was very likely somewhat greater than that of the Current Warm Period.

Luoto and Helama (2010) analyzed a sediment core extracted in October 2008 from Lake Pieni-Kauro in eastern Finland (64°17’N, 30°07’E), identifying and quantifying midge assemblages dominated by chironomids. They reconstructed a 1,500-year history of mean July air temperature from the Finnish multi-lake calibration model of Luoto (2009). The results, depicted in Figure 4.2.4.6.2.8, delineate a Medieval Warm Period stretching from about AD 580 to 1280, the peak temperature of which was approximately 0.3°C greater than the peak temperature at the end of the record, which concludes near the end of 2008.

Sundqvist *et al.* (2010) developed a 4,000-year $\delta^{18}\text{O}$ history from a stalagmite (K11) they collected in 2005 from Korallgrottan, a cave in the Caledonian mountain range of Jamtland County, northwest Sweden (64°53’N, 14°E). As shown in Figure 4.2.4.6.2.9, they demonstrated the $\delta^{18}\text{O}$ history to be well correlated with temperature, even that of the entire Northern Hemisphere.

In describing the $\delta^{18}\text{O}$ history, Sundqvist *et al.* write, “the stable isotope records show enriched isotopic values during the, for Scandinavia, comparatively cold period AD 1300–1700 [which they equate with the Little Ice Age] and depleted values during the warmer period AD 800–1000 [which they equate with the Medieval Warm Period].” As can clearly be seen from their figure, the two $\delta^{18}\text{O}$ depletion “peaks” (actually inverted valleys) of the Medieval Warm Period are both more extreme than the “peak” value of the Current Warm Period, which appears at the end of the record.

Gunnarson *et al.* (2011) write, “dendro-climatological sampling of Scots pine (*Pinus sylvestris* L.) has been made in the province of Jamtland, in the west-central Scandinavian mountains, since the 1970s,” and “a maximum latewood density (MXD) dataset, covering the period

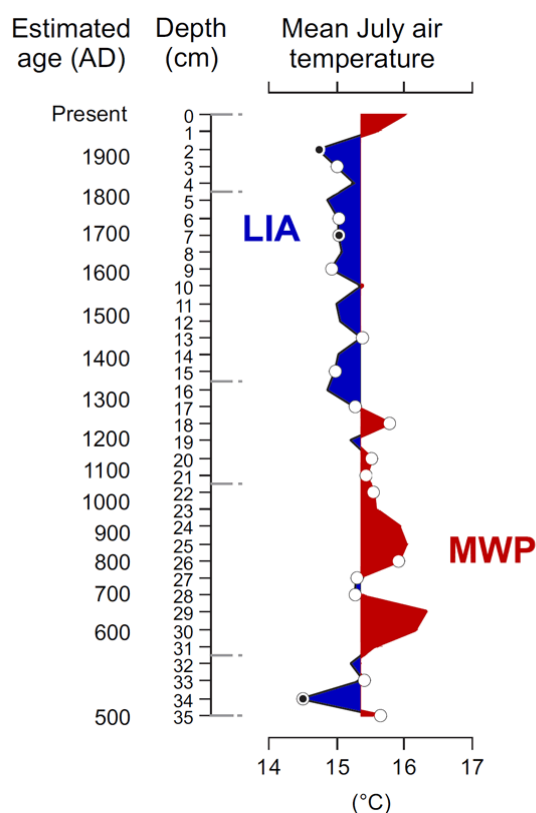


Figure 4.2.4.6.2.8. Reconstructed mean July air temperature from Lake Pieni-Kauro in eastern Finland. Adapted from Luoto, T.P. and Helama, S. 2010. Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval Climate Anomaly and Little Ice Age. *Quaternary Science Reviews* 29: 2411–2423.

AD 1107–1827 (with gap 1292–1315) was presented in the 1980s by Fritz Schweingruber.” Gunnarson *et al.* combined these older historical MXD data with “recently collected MXD data covering AD 1292–2006 into a single reconstruction of April–September temperatures for the period AD 1107–2006,” using regional curve standardization (RCS), which “provides more low-frequency variability than ‘non-RCS’ and stronger correlation with local seasonal temperatures.”

The three researchers found “a steep increase in inferred temperatures at the beginning of the twelfth century, followed by a century of warm temperatures (ca. 1150–1250),” which falls within the temporal confines of the Medieval Warm Period, and they state, “the record ends with a sharp increase in temperatures from around 1910 to the 1940s,

followed by decreasing temperatures for a few decades,” after which, they indicate, “another sharp increase in April–September temperature commenced in the late 1990s,” during what is commonly known as the Current Warm Period. They conclude “the two warmest periods are the mid to late twentieth century and the period from AD 1150–1250,” emphasizing the temperatures of both periods have been so similar that “it is not possible to conclude whether the present and relatively recent past are warmer than the 1150–1250 period.”

Divine *et al.* (2011) write, “the recent rapid climate and environmental changes in the Arctic, for instance, sea-ice retreat (e.g., Comiso *et al.*, 2008) and ice-sheet melting (e.g., van den Broeke *et al.*, 2009), require a focus on long-term variability in this area in order to view these recent changes in the long-term context.” Working with ice cores extracted from Svalbard at Lomonosovfonna in 1997 (Isaksson *et al.*, 2001) and at Høltedahlfonna in 2005 (Sjorgren *et al.*, 2007), Divine *et al.* used the $\delta^{18}\text{O}$ data derived from them to reconstruct 1,200-year winter (Dec–Feb) surface air temperature histories for nearby Longyearbyen (78.25°N, 15.47°E) and farther-afield Vardo (70.54°N, 30.61°E, in northern Norway), by calibrating (scaling) the $\delta^{18}\text{O}$ data to corresponding historically observed temperatures at the two locations, which for Longyearbyen were first collected in 1911 and for Vardo have been extended back to 1840 as a result of the work of Polyakov *et al.* (2003).

These efforts resulted in the winter surface air temperature reconstructions depicted in Figure 4.2.4.6.2.10, which begin at the peak warmth of the Medieval Warm Period at a little before AD 800. Temperatures thereafter decline fairly steadily to the coldest period of the Little Ice Age at about AD 1830, after which they rise into the 1930s, decline, and then rise again, terminating just slightly lower than their 1930s peaks near the end of the 1990s. The 11-year running-mean peak winter temperature of the Medieval Warm Period was approximately 9°C greater than the end-of-record 11-year running-mean peak winter temperature at Longyearbyen, whereas it was about 3.3°C warmer at Vardo.

Velle *et al.* (2011) used two short gravity cores and two long piston cores of sediments obtained from the deepest part of Lake Skardtjorna, Spitsbergen (77°57.780’N, 13°48.799’E) in 2008, plus a long core obtained in 2003, to reconstruct histories of chironomid types and concentrations over the past 2,000 years. They translated the chironomid data into

Observations: Temperature Records

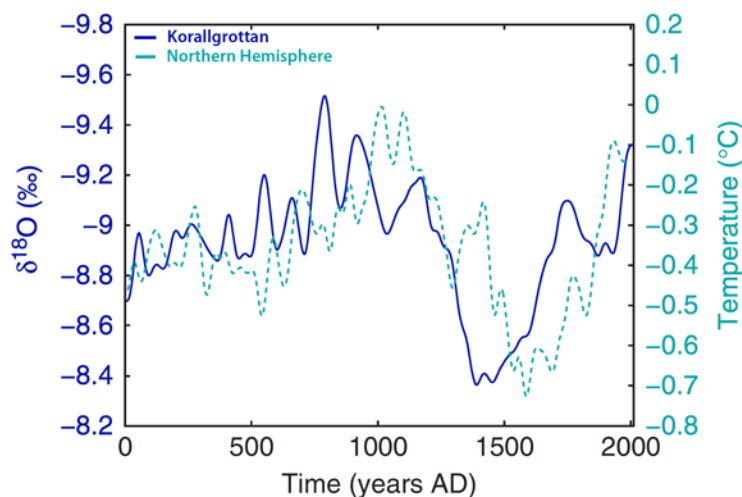


Figure 4.2.4.6.2.9. The 2,000-year Northern Hemispheric temperature reconstruction (dashed line) of Moberg *et al.* (2005) and the last half of the $\delta^{18}\text{O}$ history (solid line) developed from the K11 stalagmite. Adapted from Sundqvist, H.S., Holmgren, K., Moberg, A., Spotl, C., and Mangini, A. 2010. Stable isotopes in a stalagmite from NW Sweden document environmental changes over the past 4000 years. *Boreas* 39: 77–86.

mean July air temperatures based on a modern mean July air temperature calibration dataset compiled by Brooks and Birks (2000, 2001), plus additional unpublished data for 2001–2009, utilizing new approaches they developed for their paper. The two researchers write, a “warming that occurred at 1000 to 830 BP,” where BP = 2003, “may correspond to what is known as the ‘Medieval Warm Period.’” Their graphical representation of that record indicates the peak warmth of the MWP can be estimated to be about 0.3°C greater than the peak warmth of the Current Warm Period.

Esper *et al.* (2012) note millennial-length temperature reconstructions have become “an important source of information to benchmark climate models, detect and attribute the role of natural and anthropogenic forcing agents, and quantify the feedback strength of the global carbon cycle.” The four researchers developed 587 high-resolution wood density profiles (Frank and Esper, 2005) from living and sub-fossil *Pinus sylvestris* trees of northern Sweden and Finland to form a long-term maximum latewood density (MXD) record from 138 BC to AD 2006, in which all MXD measurements were derived from high-precision X-ray radiodensitometry, as described by Schweingruber *et al.* (1978), and where biological age trends inherent to the MXD data were removed using regional curve standardization (RCS), as described by Esper *et al.* (2003). The new MXD record was calibrated against mean June–August temperatures obtained from the long-term (1876–2006) instrumental records of Haparanda, Karasjok, and Sodankyla. Comparing their results with the earlier temperature reconstructions

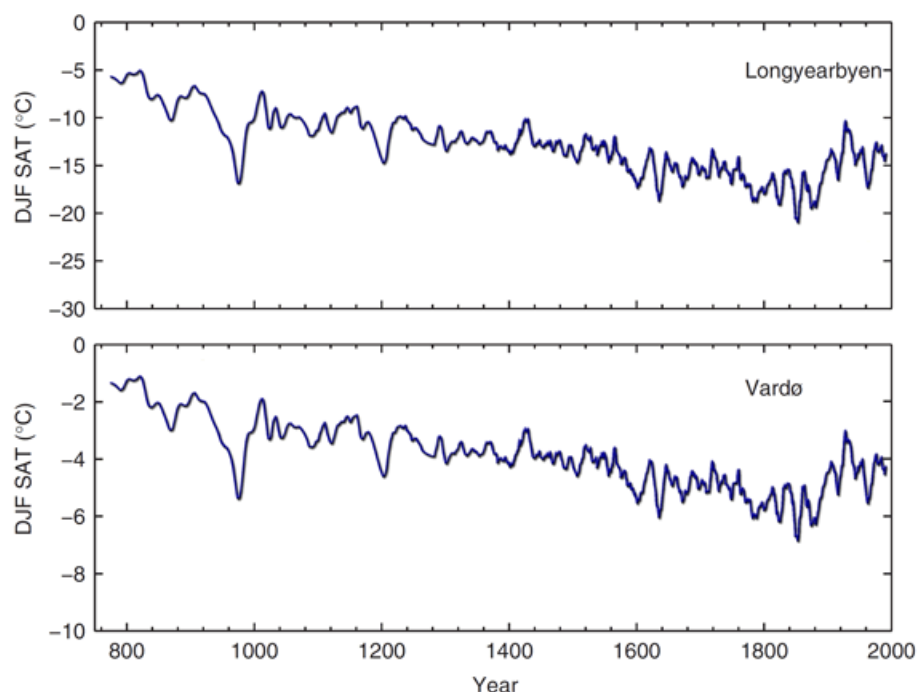


Figure 4.2.4.6.2.10. Reconstructed winter surface air temperature (SAT) for Longyearbyen (top) and Vardo (bottom) vs. time. Adapted from Divine, D., Isaksson, E., Martma, T., Meijer, H.A.J., Moore, J., Pohjola, V., van de Wal, R.S.W., and Godtlielsen, F. 2011. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. *Polar Research* 30: 10.3402/polar.v30i0.7379.

of others, they say their MXD-based summer temperature reconstruction “sets a new standard in high-resolution palaeoclimatology,” as “the record explains about 60% of the variance of regional temperature data, and is based on more high-precision density series than any other previous reconstruction.” The four researchers report their new temperature history “provides evidence for substantial warmth during Roman and Medieval times, larger in extent and longer in duration than 20th century warmth.”

References

- Allen, J.R.M., Long, A.J., Ottley, C.J., Pearson, D.G., and Huntley, B. 2007. Holocene climate variability in northernmost Europe. *Quaternary Science Reviews* **26**: 1432–1453.
- Andersson, C., Risebrobakken, B., Jansen, E., and Dahl, S.O. 2003. Late Holocene surface ocean conditions of the Norwegian Sea (Voring Plateau). *Paleoceanography* **18**: 10.1029/2001PA000654.
- Andren, E., Andren, T., and Sohlenius, G. 2000. The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. *Boreas* **29**: 233–250.
- Axford, Y., Geirsdottir, A., Miller, G.H., and Langdon, P.G. 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. *Journal of Paleolimnology* **41**: 7–24.
- Bazylinski, D.A. and Williams, T.J. 2007. Ecophysiology of magnetotactic bacteria. In: Schuler, D. (Ed.) *Magnetoreception and Magnetosomes in Bacteria*. Springer, Berlin, Germany, pp. 37–75.
- Berge, J., Johnsen, G., Nilsen, F., Gulliksen, B., and Slagstad, D. 2005. Ocean temperature oscillations enable reappearance of blue mussels *Mytilus edulis* in Svalbard after a 1000 year absence. *Marine Ecology Progress Series* **303**: 167–175.
- Berglund, B.E. 2003. Human impact and climate changes: synchronous events and a causal link? *Quaternary International* **105**: 7–12.
- Bigler, C., Barnekow, L., Heinrichs, M.L., and Hall, R.I. 2006. Holocene environmental history of Lake Vuolep Njakajaue (Abisko National Park, northern Sweden) reconstructed using biological proxy indicators. *Vegetation History and Archaeobotany* **15**: 309–320.
- Bjune, A.E., Seppa, H., and Birks, H.J.B. 2009. Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *Journal of Paleolimnology* **41**: 43–56.
- Blakemore, R.P. 1982. Magnetotactic bacteria. *Annual Review of Microbiology* **36**: 217–238.
- Blundell, A. and Barber, K. 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. *Quaternary Science Reviews* **24**: 1261–1277.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Bonnet, S., de Vernal, A., Hillaire-Marcel, C., Radi, T., and Husum, K. 2010. Variability of sea-surface temperature and sea-ice cover in the Fram Strait over the last two millennia. *Marine Micropaleontology* **74**: 59–74.
- Briffa, K.R. 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quaternary Science Reviews* **19**: 87–105.
- Brooks, S.J. and Birks, H.J.B. 2000. Chironomid-inferred late-glacial and early-Holocene mean July air temperatures for Krakenes Lake, Western Norway. *Journal of Paleolimnology* **23**: 77–89.
- Brooks, S.J. and Birks, H.J.B. 2001. Chironomid-inferred air temperatures from Late-glacial and Holocene sites in north-west Europe: progress and problems. *Quaternary Science Reviews* **20**: 1723–1741.
- Comiso, J.C., Parkinson, C.L., Gersten, R., and Stock, L. 2008. Accelerated decline in the Arctic sea ice cover. *Geophysical Research Letters* **35**: 10.1029/2007GL031972.
- Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American droughts: reconstructions, causes and consequences. *Earth Science Reviews* **81**: 93–134.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Denton, G.H. and Karlen, W. 1973. Holocene climatic variations—their pattern and possible cause. *Quaternary Research* **3**: 155–205.
- Divine, D., Isaksson, E., Martma, T., Meijer, H.A.J., Moore, J., Pohjola, V., van de Wal, R.S.W., and

Observations: Temperature Records

- Godtlieb, F. 2011. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. *Polar Research* **30**: 10.3402/polar.v30i0.7379.
- Eiriksson, J., Bartels-Jonsdottir, H.B., Cage, A.G., Gudmundsdottir, E.R., Klitgaard-Kristensen, D., Marret, F., Rodrigues, T., Abrantes, F., Austin, W.E.N., Jiang, H., Knutsen, K.-L., and Sejrup, H.-P. 2006. Variability of the North Atlantic Current during the last 2000 years based on shelf bottom water and sea surface temperatures along an open ocean/shallow marine transect in western Europe. *The Holocene* **16**: 1017–1029.
- Eronen, M., Hyvarinen, H., and Zetterberg, P. 1999. Holocene humidity changes in northern Finnish Lapland inferred from lake sediments and submerged Scots pines dated by tree-rings. *The Holocene* **9**: 569–580.
- Esper, J., Buntgen, U., Timonen, M., and Frank, D.C. 2012. Variability and extremes of northern Scandinavian summer temperatures over the past two millennia. *Global and Planetary Change* **88–89**: 1–9.
- Esper, J., Cook, E.R., Krusic, P.J., Peters, K., and Schweingruber, F.H. 2003. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Research* **59**: 81–98.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Evans, M.E. and Heller, F. 2003. *Environmental Magnetism: Principles and Applications of Environmental Magnetism*. Academic Press, Boston, Massachusetts, USA.
- Frank, D. and Esper, J. 2005. Characterization and climate response patterns of a high-elevation, multi-species tree-ring network for the European Alps. *Dendrochronologia* **22**: 107–121.
- Graham, N., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., and Xu, T. 2007. Tropical Pacific-mid-latitude teleconnections in medieval times. *Climatic Change* **83**: 241–285.
- Griffey, N.J. and Matthews, J.A. 1978. Major neoglaciation expansion episodes in southern Norway: evidences from moraine ridge stratigraphy with ¹⁴C dates on buried palaeosols and moss layers. *Geografiska Annaler* **60A**: 73–90.
- Griffey, N.J. and Worsley, P. 1978. The pattern of neoglaciation variations in the Okstindan region of northern Norway during the last three millennia. *Boreas* **7**: 1–17.
- Grubb, H. 2008. Tornetrask tree-ring width and density AD 500–2004: a test of climatic sensitivity and a new 1500-year reconstruction of north Fennoscandian summers. *Climate Dynamics*: 10.1007/s00382-0358-2.
- Grubb, H., Briffa, K.R., Karlen, W., Bartholin, T.S., Jones, P.D., and Kromer, B. 2002. A 7400-year tree-ring chronology in northern Swedish Lapland: natural climatic variability expressed on annual to millennial timescales. *The Holocene* **12**: 657–665.
- Gunnarson, B.E. and Linderholm, H.W. 2002. Low-frequency summer temperature variation in central Sweden since the tenth century inferred from tree rings. *The Holocene* **12**: 667–671.
- Gunnarson, B.E., Linderholm, H.W., and Moberg, A. 2011. Improving a tree-ring reconstruction from west-central Scandinavia: 900 years of warm-season temperatures. *Climate Dynamics* **36**: 97–108.
- Haltia-Hovi, E., Nowaczyk, N., Saarinen, T., and Plessen, B. 2010. Magnetic properties and environmental changes recorded in Lake Lehmilampi (Finland) during the Holocene. *Journal of Paleolimnology* **43**: 1–13.
- Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.
- Hammarlund, D., Barnekow, L., Birks, H.J.B., Buchardt, B., and Edwards, T.W.D. 2002. Holocene changes in atmospheric circulation recorded in the oxygen-isotope stratigraphy of lacustrine carbonates from northern Sweden. *The Holocene* **12**: 339–351.
- Hanna, E., Jonsson, T., Olafsson, J., and Vladimarsson, H. 2006. Icelandic coastal sea surface temperature records constructed: putting the pulse on air-sea-climate interactions in the Northern North Atlantic. Part I: Comparison with HadISST1 open-ocean surface temperatures and preliminary analysis of long-term patterns and anomalies of SSTs around Iceland. *Journal of Climate* **19**: 5652–5666.
- Hass, H.C. 1996. Northern Europe climate variations during late Holocene: evidence from marine Skagerrak. *Palaeogeography, Palaeoclimatology, Palaeoecology* **123**: 121–145.
- Heikkilä, M. and Seppä, H. 2003. A 11,000-yr palaeotemperature reconstruction from the southern boreal zone in Finland. *Quaternary Science Reviews* **22**: 541–554.
- Helama, S., Lindholm, M., Timonen, M., and Eronen, M. 2004. Dendrochronologically dated changes in the limit of pine in northernmost Finland during the past 7.3 millennia. *Boreas* **33**: 250–259.
- Helama, S., Meriläinen, J., and Tuomenvirta, H. 2009.

Climate Change Reconsidered II

- Multicentennial megadrought in northern Europe coincided with a global El Niño-Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* **37**: 175–178.
- Herweijer, C., Seager, R., and Cook, E.R. 2006. North American droughts of the mid to late nineteenth century: history, simulation and implications for Medieval drought. *The Holocene* **16**: 159–171.
- Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.
- Hiller, A., Boettger, T., and Kremenetski, C. 2001. Medieval climatic warming recorded by radiocarbon dated alpine tree-line shift on the Kola Peninsula, Russia. *The Holocene* **11**: 491–497.
- Hormes, A., Karlen, W., and Possnert, G. 2004. Radiocarbon dating of palaeosol components in moraines in Lapland, northern Sweden. *Quaternary Science Reviews* **23**: 2031–2043.
- Hulden, L. 2001. Ektunnor och den medeltida varmeperioden i Satakunda. *Terra* **113**: 171–178.
- Isaksson, E., Pohjola, V., Jauhiainen, T., Moore, J., Pinglot, J.-F., Vaikmae, R., van de Wal, R.S.W., Hagen, J.-O., Ivask, J., Karlof, L., Martma, T., Meijer, H.A.J., Mulvaney, R., Thomassen, M.P.A., and van den Broeke, M. 2001. A new ice core record from Lomonosovfonna, Svalbard: viewing the data between 1920–1997 in relation to present climate and environmental conditions. *Journal of Glaciology* **47**: 335–345.
- Jansen, E. and Koc, N. 2000. Century to decadal scale records of Norwegian sea surface temperature variations of the past 2 millennia. *PAGES Newsletter* **8**(1): 13–14.
- Jiang, H., Eiriksson, J., Schulz, M., Knudsen, K.L., and Seidenkrantz, M.S. 2005. Evidence for solar forcing of sea-surface temperature on the north Icelandic shelf during the late Holocene. *Geology* **33**: 73–76.
- Jiang, H., Ren, J., Knudsen, K.L., Eiriksson, J., and Ran, L.-H. 2007. Summer sea-surface temperatures and climate events on the North Icelandic shelf through the last 3000 years. *Chinese Science Bulletin* **52**: 789–796.
- Jiang, H., Seidenkrantz, M.-S., Knudsen, K.L., and Eiriksson, J. 2002. Late Holocene summer sea-surface temperatures based on a diatom record from the north Icelandic shelf. *The Holocene* **12**: 137–147.
- Justwan, A., Koc, N., and Jennings, A.E. 2008. Evolution of the Irminger and East Icelandic Current systems through the Holocene, revealed by diatom-based sea surface temperature reconstructions. *Quaternary Science Reviews* **27**: 1571–1582.
- Karlen, W. 1979. Glacier variations in the Svartisen area, northern Norway. *Geografiska Annaler* **61A**: 11–28.
- Karlen, W. and Denton, G.H. 1975. Holocene glacial variations in Sarek National Park, northern Sweden. *Boreas* **5**: 25–56.
- Karlen, W. and Kuylensstierna, J. 1996. On solar forcing of Holocene climate: evidence from Scandinavia. *The Holocene* **6**: 359–365.
- Kim, B., Kodama, K., and Moeller, R. 2005. Bacterial magnetite produced in water column dominates lake sediment mineral magnetism: Lake Ely, USA. *Geophysical Journal International* **163**: 26–37.
- Korhola, A., Weckstrom, J., Holmstrom, L., and Erasto, P. 2000. A quantitative Holocene climatic record from diatoms in Northern Fennoscandia. *Quaternary Research* **54**: 284–294.
- Kullman, L. 1998. Tree-limits and montane forests in the Swedish Scandes: Sensitive biomonitors of climate change and variability. *Ambio* **27**: 312–321.
- Kulti, S., Mikkola, K., Virtanen, T., Timonen, M., and Eronen, M. 2006. Past changes in the Scots pine forest line and climate in Finnish Lapland: a study based on megafossils, lake sediments, and GIS-based vegetation and climate data. *The Holocene* **16**: 381–391.
- Leipe, T., Dippner, J.W., Hille, S., Voss, M., Christiansen, C., and Bartholdy, J. 2008. Environmental changes in the central Baltic Sea during the past 1000 years: inferences from sedimentary records, hydrography and climate. *Oceanologia* **50**: 23–41.
- Lewis, J., Dodge, J.D., and Powell, A.J. 1990. Quaternary dinoflagellate cysts from the upwelling system offshore Peru, Hole 686B, ODP Leg 112. In: Suess, E. and von Huene, R., et al. (Eds.) *Proceedings of the Ocean Drilling Program, Scientific Results 112*. Ocean Drilling Program, College Station, TX, pp. 323–328.
- Linderholm, H.W. and Gunnarson, B.E. 2005. Summer temperature variability in central Scandinavia during the last 3600 years. *Geografiska Annaler* **87A**: 231–241.
- Luoto, T.P. and Helama, S. 2010. Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval Climate Anomaly and Little Ice Age. *Quaternary Science Reviews* **29**: 2411–2423.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Observations: Temperature Records

- Matthews, J.A. 1980. Some problems and implications of ^{14}C dates from a podzol buried beneath an end moraine at Haugabreen, southern Norway. *Geografiska Annaler* **62A**: 85–208.
- McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.
- Mikalsen, G., Sejrup, H.P., and Aarseth, I. 2001. Late-Holocene changes in ocean circulation and climate: foraminiferal and isotopic evidence from Sulafjord, western Norway. *The Holocene* **11**: 437–446.
- Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.
- Nesje, A., Dahl, S.O., Matthews, J.A., and Berrisford, M.S. 2001. A ~4500-yr record of river floods obtained from a sediment core in Lake Atnsjoen, eastern Norway. *Journal of Paleolimnology* **25**: 329–342.
- Nesje, A., Matthews, J.A., Dahl, S.O., Berrisford, M.S., and Andersson, C. 2001. Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalbreen region, western Norway, based on glaciolacustrine sediment records. *The Holocene* **11**: 267–280.
- Ojala, A.E.K. 2001. *Varved Lake Sediments in Southern and Central Finland: Long Varve Chronologies as a Basis for Holocene Palaeoenvironmental Reconstructions*. Geological Survey of Finland, Espoo.
- Paasche, O., Lovlie, R., Dahl, S.O., Bakke, J., and Nesje, E. 2004. Bacterial magnetite in lake sediments: late glacial to Holocene climate and sedimentary changes in northern Norway. *Earth and Planetary Science Letters* **223**: 319–333.
- Rein, B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.
- Roncaglia, L. 2004. Palynofacies analysis and organic-walled dinoflagellate cysts as indicators of palaeo-hydrographic changes: an example from Holocene sediments in Skalafjord, Faroe Islands. *Marine Micropaleontology* **50**: 21–42.
- Rosen, P., Segerstrom, U., Eriksson, L., Renberg, I., and Birks, H.J.B. 2001. Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjuodjijaure) in northern Sweden. *The Holocene* **11**: 551–562.
- Russell, J.M. and Johnson, T.C. 2005. A high-resolution geochemical record from Lake Edward, Uganda Congo and the timing and causes of tropical African drought during the late Holocene. *Quaternary Science Reviews* **24**: 1375–1389.
- Russell, J.M. and Johnson, T.C. 2007. Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño-Southern Oscillation variability. *Geology* **35**: 21–24.
- Saarninen, T., Tiljander, M., and Saarnisto, M. 2001. Medieval climate anomaly in Eastern Finland recorded by annually laminated lake sediments. *Monsoon* **3**: 86–89.
- Salvigsen, O. 2002. Radiocarbon dated *Mytilus edulis* and *Modiolus modiolus* from northern Svalbard: climatic implications. *Norsk Geografisk Tidsskrift* **56**: 56–61.
- Salvigsen, O., Forman, S.L., and Miller, G.H. 1992. Thermophilous mollusks on Svalbard during the Holocene and their paleoclimatic implications. *Polar Research* **11**: 1–10.
- Sangiorgi, F., Capotondi, L., and Brinkhuis, H. 2002. A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). *Palaeogeography, Palaeoclimatology, Palaeoecology* **186**: 199–216.
- Sarnthein, M., Van Kreveland, S., Erlenkreuser, H., Grootes, P.M., Kucera, M., Pflaumann, U., and Scholz, M. 2003. Centennial-to-millennial-scale periodicities of Holocene climate and sediment injections off the western Barents shelf, 75°N. *Boreas* **32**: 447–461.
- Schweingruber, F.H., Bartholin, T., Schar, E., and Briffa, K.R. 1988. Radiodensitometric-dendroclimatological conifer chronologies from Lapland (Scandinavia) and the Alps (Switzerland). *Boreas* **17**: 559–566.
- Schweingruber, F.H., Fritts, H.C., Braker, O.U., Drew, L.G., and Schaer, E. 1978. The X-ray technique as applied to dendroclimatology. *Tree-Ring Bulletin* **38**: 61–91.
- Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for Medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.
- Seppa, H. 2001. Long-term climate reconstructions from the Arctic tree-line. A NARP Symposium. *The Arctic on Thinner Ice*. 10–11 May 2001, Oulu, Finland, Abstracts, p. 29.
- Seppa, H. and Birks, H.J.B. 2001. July mean temperature and annual precipitation trends during the Holocene in the Fennoscandian tree-line area: pollen-based climate reconstruction. *The Holocene* **11**: 527–539.
- Seppa, H. and Birks, H.J.B. 2002. Holocene climate reconstructions from the Fennoscandian tree-line area based on pollen data from Toskaljavri. *Quaternary Research* **57**: 191–199.

- Shemesh, A., Rosqvist, G., Rietti-Shati, M., Rubensdotter, L., Bigler, C., Yam, R., and Karlen, W. 2001. Holocene climatic changes in Swedish Lapland inferred from an oxygen isotope record of lacustrine biogenic silica. *The Holocene* **11**: 447–454.
- Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L., Jansen, E., and Turon, J.-L. 2008. Decadal variability of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary Science Letters* **268**: 137–142.
- Sjogren, B., Brandt, O., Nuth, C., Isaksson, E., Pohjola, V.A., Kohler, J., and van de Wal, R.S.W. 2007. Determination of firn density in ice cores using image analysis. *Journal of Glaciology* **53**: 413–419.
- Snowball, I. 1994. Bacterial magnetite and the magnetic properties of sediments in a Swedish lake. *Earth and Planetary Science Letters* **126**: 129–142.
- Solanki, S.K., Usoskin, I.G., Kromer, B., Schussler, M., and Beer, J. 2004. Unusual activity of the sun during recent decades compared to the previous 11,000 years. *Nature* **431**: 1084–1087.
- Stager, J.C., Ryves, D., Cumming, B.F., Meeker, L.D., and Beer, J. 2005. Solar variability and the levels of Lake Victoria, East Africa, during the last millennium. *Journal of Paleolimnology* **33**: 243–251.
- Stancikaite, M., Sinkunas, P., Risberg, J., Seiriene, V., Blazauskas, N., Jarockis, R., Karlsson, S., and Miller, U. 2009. Human activity and the environment during the Late Iron Age and Middle Ages at the Impiltis archaeological site, NW Lithuania. *Quaternary International* **203**: 74–90.
- Stine, S. 1994. Extreme and persistent drought in California and Patagonia during medieval time. *Nature* **369**: 546–549.
- Sundqvist, H.S., Holmgren, K., Moberg, A., Spotl, C., and Mangini, A. 2010. Stable isotopes in a stalagmite from NW Sweden document environmental changes over the past 4000 years. *Boreas* **39**: 77–86.
- Tiljander, M., Saarnisto, M., Ojala, A.E.K., and Saarinen, T. 2003. A 3000-year palaeoenvironmental record from annually laminated sediment of Lake Korttajarvi, central Finland. *Boreas* **26**: 566–577.
- van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W.J., van Meijgaard, E., Velicogna, I., and Wouters, B. 2009. Partitioning recent Greenland mass loss. *Science* **326**: 984–986.
- Velle, G. 1998. *A Paleoeological Study of Chironomids (Insecta: Diptera) with Special Reference to Climate*. M.Sc. Thesis, University of Bergen.
- Velle, G., Kongshavn, K., and Birks, H.J.B. 2011. Minimizing the edge-effect in environmental reconstructions by trimming the calibration set: chironomid-inferred temperatures from Spitsbergen. *The Holocene* **21**: 417–430.
- Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. *Nature* **403**: 410–414.
- Voronina, E., Polyak, L., De Vernal, A., and Peyron, O. 2001. Holocene variations of sea-surface conditions in the southeastern Barents Sea, reconstructed from dinoflagellate cyst assemblages. *Journal of Quaternary Science* **16**: 717–726.
- Weckstrom, J., Korhola, A., Erasto, P., and Holmstrom, L. 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. *Quaternary Research* **66**: 78–86.
- Worsley, P. and Alexander, M.J. 1976. Glacier and environmental changes—neoglacial data from the outermost moraine ridges at Engabreen, Northern Norway. *Geografiska Annaler* **58**: 55–69.

4.2.4.6.3 Southern

Was there a global Medieval Warm Period? The IPCC used to acknowledge there was, but it has long since changed its view on the subject. Mounting evidence suggests it was wrong to do so. This section describes and discusses data from Southern Europe that support the IPCC's original position.

Martinez-Cortizas *et al.* (1999) analyzed a 2.5 meters-long core from the peat bog of Penido Vello in northwest Spain (43°32'N, 7°34'W), sampled at intervals of 2 cm in the upper 1 meter and at intervals of 5 cm below that depth, to derive a record of mercury deposition that extends to 4,000 radiocarbon years before the present. This work revealed “that cold climates promoted an enhanced accumulation and the preservation of mercury with low thermal stability, and warm climates were characterized by a lower accumulation and the predominance of mercury with moderate to high thermal stability.” Based on these findings and further analyses, they derived a temperature history for the region standardized to the mean temperature of the most recent 30 years of their record.

As depicted in Figure 4.2.4.6.3.1, the mean temperature of the Medieval Warm Period in northwest Spain was 1.5°C warmer than it was over the period 1968–1998, and the mean temperature of the Roman Warm Period was 2°C warmer. They also found several decadal-scale intervals during the Roman Warm Period were more than 2.5°C warmer

Observations: Temperature Records

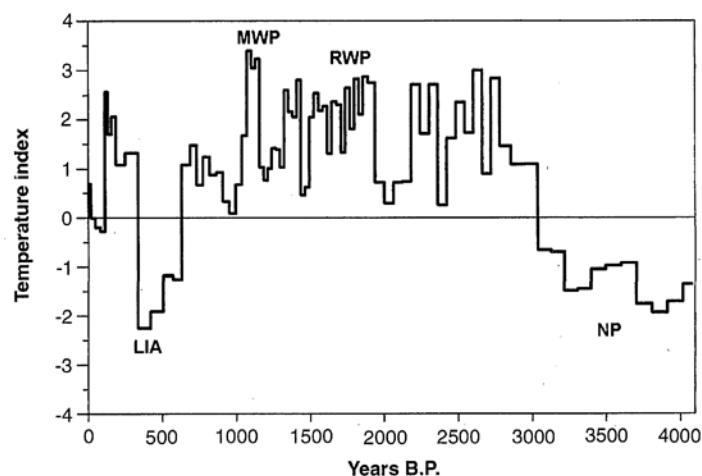


Figure 4.2.4.6.3.1. Temperature proxy for Penido Vello in northwest Spain covering the past 4,000 years. Adapted from Martinez-Cortizas, A., Pontevedra-Pombal, X., Garcia-Rodeja, E., Novoa-Muñoz, J.C., and Shoty, W. 1999. Mercury in a Spanish peat bog: archive of climate change and atmospheric metal deposition. *Science* **284**: 939–942.

than the 1968–1998 period, and an interval in excess of 80 years during the Medieval Warm Period was more than 3°C warmer. Martinez-Cortizas *et al.* conclude “for the past 4000 years ... the Roman Warm Period and the Medieval Warm Period were the most important warming periods.”

Desprat *et al.* (2003) studied the climatic variability of the last three millennia in northwest Iberia via a high-resolution pollen analysis of a sediment core retrieved from the central axis of the Ria de Vigo (42°14.07'N, 8°47.37'W) in the south of Galicia. The results suggest over the past 3,000 years there was “an alternation of three relatively cold periods with three relatively warm episodes.” In order of their occurrence, these periods are described by Desprat *et al.* as the “first cold phase of the Subatlantic period (975–250 BC),” which was “followed by the Roman Warm Period (250 BC–450 AD),” and then by “a successive cold period (450–950 AD), the Dark Ages,” which “was terminated by the onset of the Medieval Warm Period (950–1400 AD).” That was followed by “the Little Ice Age (1400–1850 AD), including the Maunder Minimum (at around 1700 AD),” which “was succeeded by the recent warming (1850 AD to the present).”

Desprat *et al.* conclude the “solar radiative budget and oceanic circulation seem to be the main mechanisms forcing this cyclicity in NW Iberia,” noting “a millennial-scale climatic cyclicity over the last 3,000 years is detected for the first time in NW

Iberia paralleling global climatic changes recorded in North Atlantic marine records (Bond *et al.*, 1997; Bianchi and McCave, 1999; Chapman and Shackleton, 2000).”

Silenzi *et al.* (2004) acquired from the northwest coast of Sicily near Capo Gallo promontory new oxygen isotopic data on sea climate trend fluctuations on Vermetid (*Dendropoma petraeum*) reefs that could be interpreted as sea surface temperature (SST) variations. These data clearly depict the Little Ice Age (LIA), with a “temperature variation of about $\Delta T = 1.99 \pm 0.37$ °C between the LIA and present day.” Of this period, they write, “Watanabe *et al.* (2001) report that ‘seawater temperature records from marine biogenic carbonate including coral and foraminifera all indicate that tropical ocean temperatures were lower by anywhere from 0.5° to 5°C during the LIA (Druffel, 1982; Glynn *et al.*, 1983; Dunbar *et al.*, 1994; Linsley *et al.*, 1994; Keigwin, 1996; Winter *et al.*, 2000) with the vast majority of studies indicating a 1–2°C change.”

Following the LIA, the data of Silenzi *et al.* reveal what they call “the warming trend that characterized the last century.” They note, “this rise in temperature ended around the years 1930–1940 AD, and was followed by a relatively cold period between the years 1940 and 1995.” Their data also indicate that in the early to mid-1500s, SSTs were warmer than they are currently, as also has been found to be the case by Keigwin (1996) and McIntyre and McKittrick (2003).

Silenzi *et al.*’s results indicate the Little Ice Age was significantly colder than what is shown by the flawed Northern Hemisphere temperature history of Mann *et al.* (1998, 1999). Moreover, Silenzi *et al.* do not show any sign of the dramatic late twentieth century warming claimed by Mann *et al.* And the work of Silenzi *et al.* indicates temperatures in the early to mid-1500s were warmer than they are currently, whereas Mann *et al.* claim it is currently warmer than it has been at any time over the past millennium or two (Mann and Jones, 2003).

Kvavadze and Connor (2005) present “some observations on the ecology, pollen productivity and Holocene history of *Zelkova carpinifolias*,” a warmth-loving tree whose pollen “is almost always accompanied by elevated proportions of thermophilous taxa,” to refine our understanding of Quaternary climatic trends. The discovery of the

tree's fossil remains in Holocene sediments, they write, "can be a good indicator of optimal climatic conditions."

The two researchers report, "Western Georgian pollen spectra of the Subatlantic period show that the period began [about 2580 cal yr BP] in a cold phase, but, by 2200 cal yr BP, climatic amelioration commenced," and "the maximum phase of warming [was] observed in spectra from 1900 cal yr BP," and this interval of warmth was Georgia's contribution to the Roman Warm Period. Thereafter, a cooler phase of climate, during the Dark Ages Cold Period, "occurred in Western Georgia about 1500–1400 cal yr BP," but it too was followed by another warm era "from 1350 to 800 years ago," the Medieval Warm Period. During portions of this time interval, they write, tree lines "migrated upwards and the distribution of *Zelkova* broadened." They also present a history of Holocene oscillations of the upper tree-line in Abkhazia, derived by Kvavadze *et al.* (1992), that depicts slightly greater-than-1950 elevations during a portion of the Medieval Warm Period and much greater extensions above the 1950 tree-line during parts of the Roman Warm Period. After the Medieval Warm Period, they report, "subsequent phases of climatic deterioration (including the Little Ice Age) ... saw an almost complete disappearance of *Zelkova* from Georgian forests."

Thus both the Roman and Medieval Warm Periods have been identified in various parts of European Georgia via studies of *Zelkova carpinifolia* pollen found in local sediments, and portions of these warm climatic intervals were likely even warmer than the conditions there during ~AD 1950, which is the "present" of Kvavadze and Connor's study.

Sea surface temperatures, river discharge, and biological productivity were reconstructed by Abrantes *et al.* (2005) in a multi-proxy analysis of a high-resolution sediment core obtained from the Tagus River estuary near

Lisbon, Portugal (~ 38.56°N, 9.35°W). The MWP was identified as occurring between AD 550 and 1300, during which mean sea surface temperatures were between 1.5 and 2°C higher than the mean value of the past century, while peak MWP warmth was about 0.9°C greater than late twentieth century peak warmth.

Pla and Catalan (2005) analyzed chrysophyte cyst data collected from 105 lakes in the Central and Eastern Pyrenees of northeast Spain to produce a history of winter/spring temperatures in this region throughout the Holocene. They found a significant oscillation in the winter/spring temperature reconstruction in which the region's climate alternated between warm and cold phases over the past several thousand years. Of particular note were the Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, and Roman Warm Period, and the warmest of these intervals was the Medieval Warm Period, which started around AD 900 and was about 0.25°C warmer than it is currently (Figure 4.2.4.6.3.2).

After the Medieval Warm Period, temperatures fell to their lowest values of the entire record (about 1.0°C below present), after which they began to warm

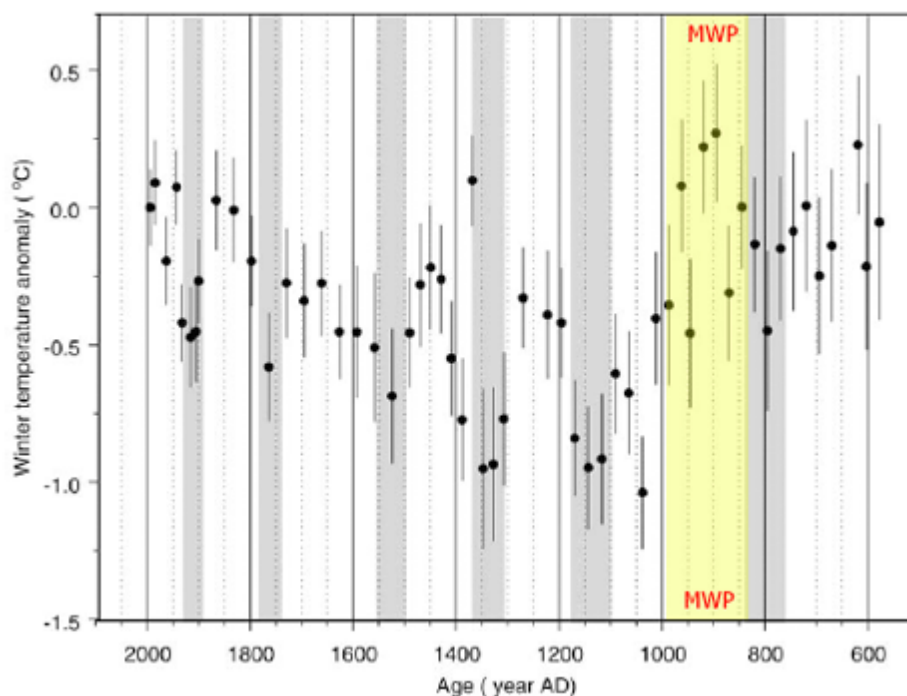


Figure 4.2.4.6.3.2. Altitude anomaly reconstruction from a chrysophyte record converted into winter/spring mean temperatures for the last 1,500 years. Adapted from Pla, S. and Catalan, J. 2005. Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* 24: 263–278.

Observations: Temperature Records

but remained below present-day values until the early nineteenth and twentieth centuries, with one exception. A significant warming was observed between 1350 and 1400, when temperatures rose a full degree Celsius to a value about 0.15°C warmer than the present. Further examination of Pla and Catalan's data reveals the Current Warm Period is not yet (and may never be) as warm as the Medieval Warm Period, for modern temperatures peaked in the 1970s–1980s and then declined throughout the 1990s.

Giraudi (2005) studied properties of alternating layers of organic-matter-rich soils and alluvial, glacial, and periglacial sediments on higher Apennine massifs in Italy, located at approximately 42°23'N, 13°31'E, reconstructing a history of relative changes in temperature for this region over the past 6,000 years. He determined organic-matter-rich soils formed on slopes currently subject to periglacial and glacial processes around 5740–5590, 1560–1370 and 1300–970 cal yr BP. Based on current relationships between elevation and soil periglacial and glacial processes, Giraudi estimates the mean annual temperature during these three periods “must therefore have been higher than at present,” and winter temperatures were at least 0.9–1.2°C higher than those of today.

Cini Castagnoli *et al.* (2005) extracted a $\delta^{13}\text{C}$ profile of *Globigerinoides ruber* from a shallow-water core in the Gulf of Taranto off the Italian coast (39°45'53"N, 17°53'33"E), which they used to produce a high-precision record of climate variability over the past two millennia. This record was statistically analyzed, together with a second two-millennia-long tree-ring record obtained from Japanese cedars (Kitagawa and Matsumoto, 1995), for evidence of recurring cycles, using Singular Spectrum Analysis and Wavelet Transform, after which both records were compared with a 300-year record of sunspots.

Plots of the pair of two-thousand-year series revealed the existence of the Dark Ages Cold Period (~400–800 AD), Medieval Warm Period (~800–1200 AD), Little Ice Age (~1500–1800 AD), and Current Warm Period. The roots of the latter period can be traced to an upswing in temperature that began in the depths of the Little Ice Age “about 1700 AD.” In addition, the statistical analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity, plus a second multidecadal oscillation (of about 93 years for the shallow-water *G. ruber* series and 87 years for the tree-ring series) in phase with the amplitude modulation of the sunspot

number series over the past 300 years.

The three researchers state the overall phase agreement between the two climate reconstructions and the variations in the sunspot number series “favors the hypothesis that the [multidecadal] oscillation revealed in $\delta^{13}\text{C}$ from the two different environments is connected to the solar activity.” This is further evidence for a solar forcing of climate at decadal and multidecadal time scales, as well as for the millennial-scale oscillation of climate that likely has been responsible for the twentieth century warming of the globe that ended the Little Ice Age and ushered in the Current Warm Period.

Frisia *et al.* (2005), working with stalagmite SV1 from Grotta Savi—a cave located at the southeast margin of the European Alps in Italy (45°37'05" N, 13°53'10" E)—developed a 17,000-year record of speleothem calcite $\delta^{18}\text{O}$ data, which they calibrated against “a reconstruction of temperature anomalies in the Alps” developed by Luterbacher *et al.* (2004) for the last quarter of the past millennium. This work revealed the occurrence of the Roman Warm Period and a Medieval Warm Period that was broken into two parts by an intervening central cold period. The five researchers state both parts of the Medieval Warm Period were “characterized by temperatures that were similar to the present.” As to the Roman Warm Period, they state, its temperatures “were similar to those of today or even slightly warmer.”

Garcia *et al.* (2007) note “despite many studies that have pointed to ... the validity of the classical climatic oscillations described for the Late Holocene (Medieval Warm Period, Little Ice Age, etc.), there is a research line that suggests the non-global signature of these periods (IPCC, 2001; Jones and Mann, 2004).” Noting “the best way to solve this controversy would be to increase the number of high-resolution records covering the last millennia and to increase the spatial coverage of these records,” they identified five distinct climatic stages: “a cold and arid phase during the Subatlantic (Late Iron Cold Period, < B.C. 150), a warmer and wetter phase (Roman Warm Period, B.C. 150–A.D. 270), a new colder and drier period coinciding with the Dark Ages (A.D. 270–900), the warmer and wetter Medieval Warm Period (A.D. 900–1400), and finally a cooling phase (Little Ice Age, >A.D. 1400).”

Noting “the Iberian Peninsula is unique, as it is located at the intersection between the Mediterranean and the Atlantic, Europe and Africa, and is consequently affected by all of them,” Garcia *et al.* suggest “the classical climatic oscillations described

for the Late Holocene (Medieval Warm Period, Little Ice Age, etc.)” were both real and global in scope. In addition, the Medieval Warm Period “is identified at about a similar date all around the world (China: Chu *et al.*, 2002; Arabia, Fleitmann *et al.*, 2004; Africa: Filippi and Talbot, 2005; Iceland: Doner, 2003; central Europe: Filippi *et al.*, 1999; New Guinea: Haberle and David, 2004; USA: Cabaniss Pederson *et al.*, 2005; Argentina: Mauquoy *et al.*, 2004; etc.,” the six scientists state, and “comparable changes are described by Desprat *et al.* (2003), Julia *et al.* (1998) and Riera *et al.* (2004) in northwest, central and northeast Spain.”

In a paper published in *Science*, Trouet *et al.* (2009) explain how they constructed a 947-year history (AD 1049–1995) of the North Atlantic Oscillation (NAO) using a tree-ring-based drought reconstruction for Morocco (Esper *et al.*, 2007) and a speleothem-based precipitation proxy for Scotland (Proctor *et al.*, 2000). This history begins in the midst of what they call the Medieval Climate Anomaly (MCA), which they describe as “a period (~AD 800–1300) marked by a wide range of changes in climate globally,” and this interval of medieval warmth is “the most recent natural counterpart to modern warmth and can therefore be used to test characteristic patterns of natural versus anthropogenic forcing.”

The results of their work are portrayed in Figure 4.2.4.6.3.3, which indicates the peak strength of the NAO during the MCA was essentially equivalent to the peak strength the NAO has so far experienced during the Current Warm Period (CWP), suggesting the peak warmth of the MCA also was likely equivalent to the peak warmth of the CWP.

With respect to what caused the development of medieval warmth throughout Europe, Trouet *et al.* write “the increased pressure difference between the Azores High and the Icelandic Low during positive NAO phases results in enhanced zonal flow, with stronger westerlies transporting warm air to the European continent,” to which they add, “stronger westerlies associated with a positive NAO phase may have enhanced the Atlantic meridional overturning circulation (AMOC),” which in turn may have generated “a related northward migration of the intertropical convergence zone.”

As for what might have initiated these phenomena, Trouet *et al.* say “the persistent positive phase [of the NAO] reconstructed for the MCA appears to be associated with prevailing La Niña-like conditions possibly initiated by enhanced solar

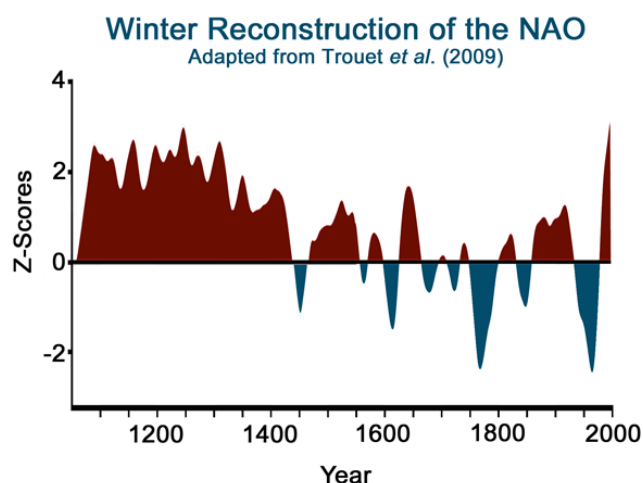


Figure 4.2.4.6.3.3. Winter reconstruction of the NAO over the past 1,000 years. Adapted from Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* 324: 78–80.

irradiance and/or reduced volcanic activity and amplified and prolonged by enhanced AMOC.” That explanation is highly plausible, especially in light of the many paleoclimate studies that have identified cyclical solar activity as the primary cause of various climate cycles (see Chapter 3, this volume). The six scientists conclude, “the relaxation from this particular ocean-atmosphere state [that of the MCA] into the Little Ice Age appears to be globally contemporaneous and suggests a notable and persistent reorganization of large-scale oceanic and atmospheric circulation patterns.” Consequently, it is equally reasonable to suggest the reversal of this process—the reinstatement of the particular ocean-atmosphere state that characterized the MCA—may be what has led to the globally contemporaneous development of the Current Warm Period. This scenario suggests the planet’s current level of relative warmth may be due to processes originating in the Sun, which are of course not attributable to man.

Geirsdottir *et al.* (2009) studied biogenic silica (BSi) and total organic carbon (TOC) data obtained from two sediment cores retrieved from Haukadalsvatn (65°03.064’N, 21°37.830’W), a lake in northwest Iceland, and a 170-year instrumental temperature history obtained from Stykkisholmur (50 km distant). They identified “a broad peak in BSi and lack of a trend in TOC between ca. 900 and 1200 AD,” which they describe as being indicative of “a

Observations: Temperature Records

broad interval of warmth” “coincident with the Medieval Warm Period,” which clearly exhibited greater warmth than was observed at any time during the Current Warm Period (see Figure 4.2.4.6.3.4).

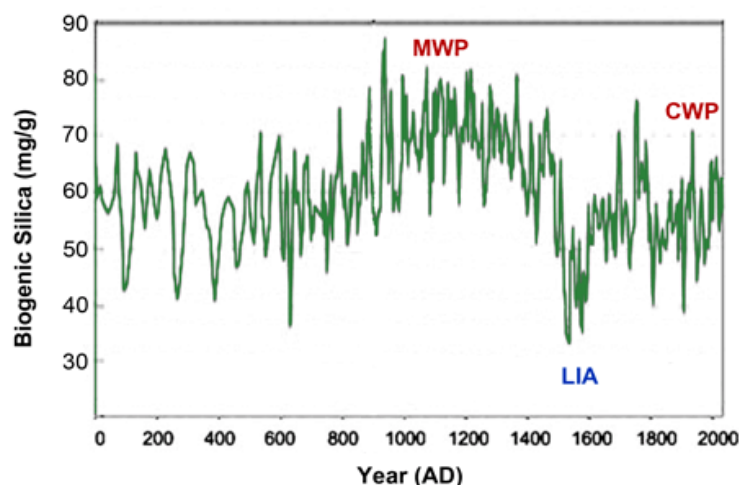


Figure 4.2.4.6.3.4. A 2,000-year record of climate variations reconstructed from Haukadalsvatn, West Iceland. Adapted from Geirsdottir, A., Miller, G.H., Thordarson, T., and Olafsdottir, K.B. 2009. A 2000-year record of climate variations reconstructed from Haukadalsvatn, West Iceland. *Journal of Paleolimnology* 41: 95–115.

Giraudi (2009) examined “long-term relations among glacial activity, periglacial activity, soil development in northwestern Italy’s alpine River Orco headwaters, and down-valley floods on the River Po,” based on “studies carried out by means of geological and geomorphologic surveys on the glacial and periglacial features,” including a sampling of soils involved in periglacial processes that “provided a basis for development of a chronological framework of late Holocene environmental change” and an analysis of “a stratigraphic sequence exposed in a peat bog along the Rio del Nel” about 1 km from the front edge of the Eastern Nel Glacier.

Giraudi determined between about 200 BC and AD 100—i.e., during the Roman Warm Period—“soils developed in areas at present devoid of vegetation and with permafrost,” indicating temperatures at that time “probably reached higher values than those of the present.” He also concludes, “analogous conditions likely occurred during the period of [the] 11th–12th centuries AD, when a soil developed on a slope presently characterized by periglacial debris,” while noting “in the 11th–12th centuries AD, frost weathering processes were not

active and, due to the higher temperatures than at present or the longer duration of a period with high temperatures, vegetation succeeded in colonizing the slope.” He also found “the phase of greatest glacial expansion (Little Ice Age) coincides with a period characterized by a large number of floods in the River Po basin,” and “phases of glacial retreat [such as occurred during the Roman and Medieval Warm Periods] correlate with periods with relatively few floods in the River Po basin.”

Martin-Chivelet *et al.* (2011) developed a 4,000-year temperature history for the northern part of Castilla-Leon in northern Spain based on $\delta^{13}\text{C}$ data obtained from stalagmites recovered from three caves, each of which was situated approximately 50 km from a common central point ($\sim 42^\circ 40' \text{N}$, 4°W), having found good correlation between the mean annual temperatures of the past 125 years (from a site located 14 km from one of the caves) and corresponding $\delta^{13}\text{C}$ data. According to the five researchers, their $\delta^{13}\text{C}$ record began with “an initial interval of broad warm conditions between 4000 and 3000 yr BP.” Then came “a prolonged time during which thermal conditions become permanently cold,” with the coldest conditions occurring between 2,850 and 2,550 yr BP, an interval they describe as “the ‘first cold phase’ of the Subatlantic period, also called in Europe the Iron Age Cold Period.” Next came another warm period when “maximum temperatures were probably reached in the three hundred years interval between 2150 and 1750 yr BP,” which corresponds, they write, “to the well-known Roman Warm Period, an interval which has been correlated with a phase of relatively high solar flux.”

Thereafter came “another relatively cold episode, which lasted about 250 years and reached its minimum at ~ 1500 yr BP,” which “correlated with the Dark Ages Cold Period described in other areas of Europe.” Then, “a rapid trend of warming led to a new, prolonged interval of warmth” that lasted from 1,400 to 700 yr BP. Martin-Chivelet *et al.* state this Medieval Warm Period is “probably the most robust climatic feature in our records, perfectly outlined in the series of the three stalagmites.” They also note, “the end of the Medieval Warm Period was marked by a progressive and rapid ... transition into the Little Ice Age, a relatively cold period broadly reported from all Europe and also from other areas in the

world as far as South Africa or South America.”

A graph of the researchers’ data portrays the development of the Current Warm Period, and it suggests temperatures at the end of the twentieth century were about a quarter of a degree Centigrade warmer than the peak warmth of the Medieval Warm Period. They note studies in Northern Spain based on peat bog proxies “suggest that the temperatures during both the Roman Warm Period and the Medieval Warm Period were higher than present-day ones,” citing Martinez-Cortizas *et al.* (1999).

Andrade *et al.* (2011) worked with a 2.5-m gravity core and an 18-cm box core taken from the outer area of the Ria de Muros (42°44’N, 9°02’W) on the northwestern coast of the Iberian Peninsula in June 2004 to establish a climate history of the region through “the combined use of textural analysis, magnetic properties and geochemical parameters (total concentrations of diagenetically stable and mobile elements in sediment and pore water),” which “allowed the identification of a current redox front and two palaeosedimentary redox fronts in the sediment record.”

These three redox fronts, as the team of Spanish scientists describe them, “originated during periods of high marine/terrestrial organic matter ratio (as inferred from the ratio of total organic carbon to total nitrogen and $\delta^{13}\text{C}$).” They state, “sedimentation rates calculated from ^{14}C dating results identify these periods as known periods of increased upwelling and reduced continental input due to colder, drier climate in the NW Iberian Peninsula, namely the Little Ice Age, the Dark Ages, and the first cold period of the Upper Holocene.” They also point out the lower proportion of oceanic influence observed between 1,250 and 560 cal. yr BP “coincides with the Medieval Warm Period, during which there was an increase in continental input to both the continental shelf (Mohamed *et al.*, 2010) and the Rias of Vigo and Muros (Alvarez *et al.*, 2005; Lebreiro *et al.*, 2006).” Finally, they note the colder Dark Ages period was preceded by the “Roman Warm Period.”

Morellon *et al.* (2011) write, “in the context of present-day global warming, there is increased interest in documenting climate variability during the last millennium,” because “it is crucial to reconstruct pre-industrial conditions to discriminate anthropogenic components (i.e., greenhouse gases, land-use changes) from natural forcings (i.e., solar variability, volcanic emissions).” They conducted a multi-proxy study of several short sediment cores recovered from Lake Estanya (42°02’N, 0°32’E) in the Pre-Pyrenean

Ranges of northeast Spain, which provide “a detailed record of the complex environmental, hydrological and anthropogenic interactions occurring in the area since medieval times.” They report, “the integration of sedimentary facies, elemental and isotopic geochemistry, and biological proxies (diatoms, chironomids and pollen), together with a robust chronological control, provided by AMS radiocarbon dating and ^{210}Pb and ^{137}Cs radiometric techniques, enabled precise reconstruction of the main phases of environmental change, associated with the Medieval Warm Period (MWP), the Little Ice Age (LIA) and the industrial era.”

The 13 researchers identified the MWP as occurring in their record from AD 1150 to 1300, noting their pollen data reflect “warmer and drier conditions,” in harmony with the higher temperatures of the Iberian Peninsula over the same period that have been documented by Martinez-Cortizas *et al.* (1999), the higher temperatures of the Western Mediterranean region found by Taricco *et al.* (2008), and the global reconstructions of Crowley and Lowery (2000) and Osborn and Briffa (2006), all of which “clearly document warmer conditions from the twelfth to fourteenth centuries.” This warmth, Morellon *et al.* state, is “likely related to increased solar irradiance (Bard *et al.*, 2000), persistent La Niña-like tropical Pacific conditions, a warm phase of the Atlantic Multidecadal Oscillation, and a more frequent positive phase of the North Atlantic Oscillation (Seager *et al.*, 2007).”

Following the MWP was the LIA, which Morellon *et al.* recognize as occurring from AD 1300 to 1850. Lower temperatures (Martinez-Cortizas *et al.*, 1999) characterized this period on the Iberian Peninsula, which “coincided with colder North Atlantic (Bond *et al.*, 2001) and Mediterranean sea surface temperatures (Taricco *et al.*, 2008) and a phase of mountain glacier advance (Wanner *et al.*, 2008),” they report. Following the LIA they identified the transition period of AD 1850–2004, which took the region into the Current Warm Period.

Morellon *et al.* write, “a comparison of the main hydrological transitions during the last 800 years in Lake Estanya and solar irradiance (Bard *et al.*, 2000) reveals that lower lake levels dominated during periods of enhanced solar activity (MWP and post-1850 AD) and higher lake levels during periods of diminished solar activity (LIA).” Within the LIA, they note periods of higher lake levels or evidence of increased water balance occurred during the solar minima of Wolf (AD 1282–1342), Sporer (AD 1460–

Observations: Temperature Records

1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1830).

In light of these observations, it appears the multi-centennial climate oscillation uncovered by the 13 researchers has been driven by a similar oscillation in solar activity and by multi-decadal solar activity fluctuations superimposed on that longer-period oscillation. These relationships suggest there is no compelling reason to attribute twentieth century global warming to the concomitant increase in the air's CO₂ content.

As noted in this section, a significant body of research documents the existence of the millennial-scale oscillation of climate that has alternately brought Earth both into and out of the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, and Little Ice Age, and, most recently, into the Current Warm Period. During these climatic transitions, except for the most recent one, there have been no significant changes in the atmosphere's CO₂ concentration, which suggests the transition out of the Little Ice Age and into the Current Warm Period likely had nothing at all to do with the concomitant increase in the air's CO₂ content.

References

- Abrantes, F., Lebreiro, S., Rodrigues, T., Gil, I., Bartels-Jónsdóttir, H., Oliveira, P., Kissel, C., and Grimalt, J.O. 2005. Shallow-marine sediment cores record climate variability and earthquake activity off Lisbon (Portugal) for the last 2000 years. *Quaternary Science Reviews* **24**: 2477–2494.
- Alvarez, M.C., Flores, J.A., Sierro, F.J., Diz, P., Frances, G., Pelejero, C., and Grimalt, J. 2005. Millennial surface water dynamics in the Ria de Vigo during the last 3000 years as revealed by coccoliths and molecular biomarkers. *Palaeogeography, Palaeoclimatology, Palaeoecology* **218**: 1–13.
- Andrade, A., Rubio, B., Rey, D., Alvarez-Iglesias, P., Bernabeu, A.M., and Vilas, F. 2011. Palaeoclimatic changes in the NW Iberian Peninsula during the last 3000 years inferred from diagenetic proxies in the Ria de Muros sedimentary record. *Climate Research* **48**: 247–259.
- Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus* **52B**: 985–992.
- Bianchi, G.G. and McCave, I.N. 1999. Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland. *Nature* **397**: 515–517.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Cabaniss Pederson, D., Peteet, D.M., Kurdyla, D., and Guilderson, T. 2005. Medieval warming, Little Ice Age, and European impact on the environment during the last millennium in the lower Hudson Valley, New York, USA. *Quaternary Research* **63**: 238–249.
- Chapman, M.R. and Shackleton, N.L. 2000. Evidence of 550-year and 1000-year cyclicities in North Atlantic circulation patterns during the Holocene. *The Holocene* **10**: 287–291.
- Chu, G., Li, J., Sun, O., Lu, H., Gu, Z., Wang, W., and Liu, T. 2002. The “Mediaeval Warm Period” drought recorded in Lake Huguangyan, tropical South China. *The Holocene* **12**: 511–516.
- Cini Castagnoli, G., Taricco, C., and Alessio, S. 2005. Isotopic record in a marine shallow-water core: Imprint of solar centennial cycles in the past 2 millennia. *Advances in Space Research* **35**: 504–508.
- Crowley, T.J. and Lowery, T.S. 2000. How warm was the Medieval Warm Period? *Ambio* **29**: 51–54.
- Desprat, S., Goñi, M.F.S., and Loutre, M.-F. 2003. Revealing climatic variability of the last three millennia in northwestern Iberia using pollen influx data. *Earth and Planetary Science Letters* **213**: 63–78.
- Doner, L. 2003. Late-Holocene paleoenvironments of northwest Iceland from lake sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology* **193**: 535–560.
- Druffel, E.M. 1982. Banded corals: change in oceanic carbon-14 during the Little Ice Age. *Science* **218**: 13–19.
- Dunbar, R.B., Wellington, G.M., Colgan, M.W., and Peter, W. 1994. Eastern Pacific sea surface temperature since 1600 AD: the $\delta^{18}\text{O}$ record of climate variability in Galapagos corals. *Paleoceanography* **9**: 291–315.
- Esper, J., Frank, D., Buntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E. 2007. Long-term drought severity variations in Morocco. *Geophysical Research Letters* **34**: 10.1029/2007GL030844.
- Filippi, M.L., Lambert, P., Hunziker, J., Kubler, B., and Bernasconi, S. 1999. Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millennia. *Journal of Paleolimnology* **21**: 19–34.

Climate Change Reconsidered II

- Filippi, M.L. and Talbot, M.R. 2005. The palaeolimnology of northern Lake Malawi over the last 25 ka based upon the elemental and stable isotopic composition of sedimentary organic matter. *Quaternary Science Reviews* **24**: 1303–1328.
- Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., and Matter, A. 2004. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from Southern Oman. *Quaternary Science Reviews* **23**: 935–945.
- Frisia, S., Borsato, A., Spotl, C., Villa, I.M., and Cucchini, F. 2005. Climate variability in the SE Alps of Italy over the past 17,000 years reconstructed from a stalagmite record. *Boreas* **34**: 445–455.
- Garcia, M.J.G., Zapata, M.B.R., Santisteban, J.I., Mediavilla, R., Lopez-Pamo, E., and Dabrio, C.J. 2007. *Vegetation History and Archaeobotany* **16**: 241–250.
- Geirsdottir, A., Miller, G.H., Thordarson, T., and Olafsdottir, K.B. 2009. A 2000-year record of climate variations reconstructed from Haukadalsvatn, West Iceland. *Journal of Paleolimnology* **41**: 95–115.
- Giraudi, C. 2005. Middle to Late Holocene glacial variations, periglacial processes and alluvial sedimentation on the higher Apennine massifs (Italy). *Quaternary Research* **64**: 176–184.
- Giraudi, C. 2009. Late Holocene glacial and periglacial evolution in the upper Orco Valley, northwestern Italian Alps. *Quaternary Research* **71**: 1–8.
- Glynn, P.W., Druffel, E.M., and Dunbar, R.B. 1983. A dead Central American coral reef tract: possible link with the Little Ice Age. *Journal of Marine Research* **41**: 605–637.
- Haberle, S.G. and David, B. 2004. Climates of change: human dimensions of Holocene environmental change in low latitudes of the PEPH transect. *Quaternary International* **118**: 165–179.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.
- Jones, P.D. and Mann, M.E. 2004. Climate over past millennia. *Reviews of Geophysics* **42**: 10.1029/2003RG000143.
- Julia, R., Burjachs, F., Dasi, M.J., Mezquita, F., Miracle, M.R., Roca, J.R. Seret, G., and Vicente, E. 1998. Meromixis origin and recent trophic evolution in the Spanish mountain lake La Cruz. *Aquatic Sciences* **60**: 279–299.
- Keigwin, L.D. 1996. The little ice age and medieval warm period in the Sargasso Sea. *Science* **274**: 1504–1508.
- Kitagawa, H. and Matsumoto, E. 1995. Climatic implications of $\delta^{13}\text{C}$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.
- Kvavadze, E.V., Bukreeva, G.F., and Rukhadze, L.P. 1992. *Komp'uternaia Tekhnologia Rekonstruktsii Paleogeograficheskikh Rekonstruktsii V Gorakh (na primere golotsena Abkhazii)*. Metsniereba, Tbilisi.
- Kvavadze, E.V. and Connor, S.E. 2005. *Zelkova carpinifolia* (Pallas) K. Koch in Holocene sediments of Georgia—an indicator of climatic optima. *Review of Palaeobotany and Palynology* **133**: 69–89.
- Lebreiro, S.M., Frances, G., Abrantes, F.F.G., Diz, P., Bartels-Jonsdottir, H.B., Stroynowski, Z.N., Gil, I.M., Pena, L.D., Rodrigues, T., Jones, P.D., Nombela, M.A., Alejo, I., Briffa, K.R., Harris, I., and Grimalt, J.O. 2006. Climate change and coastal hydrographic response along the Atlantic Iberian margin (Tagus Prodelta and Muros Ria) during the last two millennia. *The Holocene* **16**: 1003–1015.
- Linsley, B.K., Dunbar, R.B., Wellington, G.M., and Mucciarone, D.A. 1994. A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707. *Journal of Geophysical Research* **99**: 9977–9994.
- Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* **303**: 1499–1503.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.
- Martin-Chivelet, J., Munoz-Garcia, M.B., Edwards, R.L., Turrero, M.J., and Ortega, A.I. 2011. Land surface temperature changes in Northern Iberia since 4000 yr BP, based on $\delta^{13}\text{C}$ of speleothems. *Global and Planetary Change* **77**: 1–12.
- Martinez-Cortizas, A., Pontevedra-Pombal, X., Garcia-Rodeja, E., Novoa-Muñoz, J.C., and Shotyk, W. 1999. Mercury in a Spanish peat bog: archive of climate change and atmospheric metal deposition. *Science* **284**: 939–942.
- Mauquoy, D., Blaauw, M., van Geel, B., Borromei, A.,

Observations: Temperature Records

Quattrocchio, M., Chambers, F., and Possnert, G. 2004. Late Holocene climatic changes in Tierra del Fuego based on multiproxy analyses of peat deposits. *Quaternary Research* **61**: 148–158.

McIntyre, S. and McKittrick, R. 2003. Corrections to the Mann *et al.* (1998) proxy data base and Northern Hemispheric average temperature series. *Energy & Environment* **14**: 751–771.

Mohamed, K.J., Rey, D., Rubio, B., Vilas, F., and Frederichs, T. 2010. Interplay between detrital and diagenetic processes since the last glacial maximum on the northwest Iberian continental shelf. *Quaternary Research* **73**: 507–520.

Morellon, M., Valero-Garcés, B., Gonzalez-Samperiz, P., Vegas-Vilarrubia, T., Rubio, E., Rieradevall, M., Delgado-Huertas, A., Mata, P., Romero, O., Engstrom, D.R., Lopez-Vicente, M., Navas, A., and Soto, J. 2011. Climate changes and human activities recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age. *Journal of Paleolimnology* **46**: 423–452.

Osborn, T.J. and Briffa, K.R. 2006. The spatial extent of 20th-century warmth in the context of the past 1200 years. *Science* **311**: 841–844.

Pla, S. and Catalan, J. 2005. Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* **24**: 263–278.

Proctor, C.J., Baker, A., Barnes, W.L., and Gilmour, M.A. 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Riera, S., Wansard, G., and Julia, R. 2004. 2000-year environmental history of a karstic lake in the Mediterranean Pre-Pyrenees: the Estanya lakes (Spain). *Catena* **55**: 293–324.

Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.

Silenzi, S., Antonioli, F., and Chemello, R. 2004. A new marker for sea surface temperature trend during the last centuries in temperate areas: Vermetid reef. *Global and Planetary Change* **40**: 105–114.

Taricco, C., Ghil, M., and Vivaldo, G. 2008. Two millennia of climate variability in the Central Mediterranean. *Climate of the Past Discussions* **4**: 1089–1113.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* **324**: 78–80.

Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid- to late Holocene climate change: an overview. *Quaternary Science Reviews* **27**: 1791–1828.

Watanabe, T., Winter, A., and Oba, T. 2001. Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and ¹⁸O/¹⁶O ratios in corals. *Marine Geology* **173**: 21–35.

Winter, A., Ishioroshi, H., Watanabe, T., Oba, T., and Christy, J.R. 2000. A two-to-three degree cooling of Caribbean Sea surface temperatures during the Little Ice Age. *Geophysical Research Letters* **27**: 3365–3358.

4.2.4.7 North America

As indicated in the introduction of Section 4.2.4, numerous peer-reviewed studies reveal modern temperatures are not unusual. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO₂ content remained at values approximately 30 percent lower than that of today.

The following subsections highlight evidence from North America, where much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, then the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; Current Warm Period is simply a manifestation of its latest phase. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

4.2.4.7.1 Alaska and Canada

Arseneault and Payette (1997) analyzed tree-ring and growth-form sequences obtained from more than 300 spruce remains buried in currently treeless peatland located near the tree line in northern Québec to produce a proxy record of climate for this region between AD 690 and 1591. Over this 900-year period, the trees of the region experienced several episodes of both suppressed and rapid growth,

indicative of colder and warmer conditions, respectively, than those of the present, the scientists found. Cooler (suppressed growth) conditions prevailed in AD 760–860 and 1025–1400, and warmer (rapid growth) conditions were prevalent in AD 700–750, 860–1000, 1400–1450, and 1500–1570.

Further analysis of the warm period between AD 860 and 1000 led the two researchers to conclude the warmth experienced in northern Quebec during this period coincided with the Medieval Warm Period experienced across the North Atlantic and Northern Europe, which “exceeded in duration and magnitude both the 16th and 20th century warm periods identified previously [by other scientists] using the same methods.” Furthermore, on the basis of current annual temperatures at their study site and the northernmost twentieth century location of the forest, which at that time was 130 km south of their site, they conclude, the “Medieval Warm Period was approximately 1°C warmer than the 20th century.”

Campbell and Campbell (2000) analyzed pollen and charcoal records obtained from sediment cores retrieved from three small ponds—South Pond (AD 1655–1993), Birch Island Pond (AD 1499–1993), and Pen 5 Pond (400 BC–AD 1993)—located within Canada’s Elk Island National Park, which covers close to 200 km² of the Beaver Hills region of east-central Alberta. Contrary to the intuitive assumption that there would be an “increase in fire activity with warmer and drier climate,” the Canadian researchers found “declining groundwater levels during the Medieval Warm Period [MWP] allowed the replacement of substantial areas of shrub birch with the less fire-prone aspen, causing a decline in fire frequency and/or severity, while increasing carbon storage on the landscape.” They conclude this scenario “is likely playing out again today,” as all three of the sites they studied “show historic increases in *Populus* pollen and declines in charcoal.”

The two researchers note Earth’s present climate “is warmer and drier than that of either the Little Ice Age (which followed the MWP) or the early Neoglacial (preceding the MWP),” and we must therefore “consider the present pond levels to be more representative of the MWP than of the time before or after.” But since their Pen 5 Pond data indicate sediment charcoal concentrations have not yet dropped to the level characteristic of the MWP—even with what they describe as the help of “active fire suppression in the park combined with what may be thought of as unintentional fire suppression due to agricultural activity around the park”—it appears

their study sites and their surroundings have not yet risen to the level of warmth and dryness of the MWP, which they describe as having occurred over the period AD 800–1200.

Calkin *et al.* (2001) reviewed what they called “the most current and comprehensive research of Holocene glaciation” along the northernmost Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, noting several periods of glacial advance and retreat during the past 7,000 years. They describe a general retreat during the Medieval Warm Period that lasted for “at least a few centuries prior to AD 1200.” After this Medieval Climatic Optimum, there were three major intervals of Little Ice Age glacial advance: the early fifteenth century, middle seventeenth century, and the last half of the nineteenth century. During these latter periods, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers “reached their Holocene maximum extensions.”

The existence of a Medieval Warm Period and Little Ice Age in Alaska is an obvious reality. Glaciers there reached their maximum Holocene extensions during the Little Ice Age, and it can be inferred Alaskan temperatures reached their Holocene minimum during this period as well. It should therefore come as no surprise that temperatures in Alaska rose significantly above the chill of the Little Ice Age in the region’s natural recovery from the coldest period of the Holocene.

Hu *et al.* (2001) “conducted multi-proxy geochemical analyses of a sediment core from Farewell Lake in the northwestern foothills of the Alaska Range,” obtaining what they describe as “the first high-resolution quantitative record of Alaskan climate variations that spans the last two millennia.” The team of five scientists report their results “suggest that at Farewell Lake SWT [surface water temperature] was as warm as the present at AD 0–300 [during the Roman Warm Period], after which it decreased steadily by ~3.5°C to reach a minimum at AD 600 [during the depths of the Dark Ages Cold Period].” From then, they state, “SWT increased by ~3.0°C during the period AD 600–850 and then [during the Medieval Warm Period] exhibited fluctuations of 0.5–1.0°C until AD 1200.” Completing their narrative, they write, “between AD 1200–1700, SWT decreased gradually by 1.25°C [as the world descended into the depths of the Little Ice Age], and from AD 1700 to the present, SWT increased by 1.75°C,” the latter portion of which

Observations: Temperature Records

warming initiated the Current Warm Period.

Hu *et al.* remark, “the warmth before AD 300 at Farewell Lake coincides with a warm episode extensively documented in northern Europe ... whereas the AD 600 cooling is coeval with the European ‘Dark Ages.’” They also report, “the relatively warm climate AD 850–1200 at Farewell Lake corresponds to the Medieval Climatic Anomaly, a time of marked climatic departure over much of the planet.” They note “these concurrent changes suggest large-scale teleconnections in natural climatic variability during the last two millennia, likely driven by atmospheric controls.”

Noting “20th-century climate is a major societal concern in the context of greenhouse warming,” Hu *et al.* conclude by reiterating their record “reveals three time intervals of comparable warmth: AD 0–300, 850–1200, and post-1800,” and they write, “these data agree with tree-ring evidence from Fennoscandia, indicating that the recent warmth is not atypical of the past 1000 years.”

These observations testify to the reality of the non-CO₂-induced millennial-scale oscillation of climate that brought the world, including Alaska, significant periods of warmth some 1,000 years ago, during the Medieval Warm Period, and some 1,000 years before that, during the Roman Warm Period. These earlier periods of warmth were unquestionably not caused by elevated atmospheric CO₂ concentrations, nor were they due to elevated concentrations of any other greenhouse gases. They were caused by something else, and the warmth of today could be due to that same cause.

Gedalof and Smith (2001) compiled a transect of six tree ring-width chronologies from stands of mountain hemlock growing near the treeline that extends from southern Oregon to the Kenai Peninsula, Alaska, analyzing the data in such a way as to “directly relate changes in radial growth to annual variations in the North Pacific ocean-atmosphere system.” Over the period of their study (AD 1599–1983), they determined “much of the pre-instrumental record in the Pacific Northwest region of North America [was] characterized by alternating regimes of relatively warmer and cooler SST [sea surface temperature] in the North Pacific, punctuated by abrupt shifts in the mean background state,” which were found to be “relatively common occurrences.” They found “regime shifts in the North Pacific have occurred 11 times since 1650.” Significantly, the abrupt 1976–1977 shift in this Pacific Decadal Oscillation, as it is generally called, was found to be

responsible for the vast majority of the past half-century’s warming in Alaska.

Kaplan *et al.* (2002) reported on paleolimnological inferences regarding Holocene climatic variability from a small lake in southern Greenland—Qipisarqo Lake (61°00’41”N, 47°45’13”W)—based on lake sediment physical-chemical properties, including magnetic susceptibility, density, water content, and biogenic silica and organic matter concentration. They found “the interval from 6000 to 3000 cal yr B.P. was marked by warmth and stability.” Thereafter, however, the climate cooled “until its culmination during the Little Ice Age.” From 1,300 to 900 cal yr B.P., there was a partial amelioration during the Medieval Warm Period, which was associated with an approximate 1.5°C rise in temperature. Then, after another brief warming between A.D. 1500 and 1750, the second and more severe portion of the Little Ice Age occurred, which in turn was followed by “naturally initiated post-Little Ice Age warming since A.D. 1850, which is recorded throughout the Arctic” and “has not yet reached peak Holocene warmth.”

The three researchers note “colonization around the northwestern North Atlantic occurred during peak Medieval Warm Period conditions that ended in southern Greenland by AD 1100.” Norse movements around the region thereafter occurred at what they describe as “perhaps the worst time in the last 10,000 years, in terms of the overall stability of the environment for sustained plant and animal husbandry.” The demise of the Norse colonies clearly was the result of “the most environmentally unstable period since deglaciation.” They conclude, “current warming, however rapid, has not yet reached peak Holocene warmth.”

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Alberta’s Pine Lake (52°N, 113.5°W) to provide a non-vegetation-based high-resolution record of climate variability for this part of North America over the past 4,000 years. This effort revealed periods of both increasing and decreasing grain size (moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales, with the most predominant departures including four several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500–1900), Medieval Warm Period (about AD 700–1300), Dark Ages Cold Period (about 100 BC to AD 700), and Roman Warm Period (about 900–100 BC). A standardized median grain-size history indicated the highest rates of stream

discharge during the past 4,000 years occurred during the Little Ice Age at approximately 300–350 years ago, when grain sizes were about 2.5 standard deviations above the 4,000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2 standard deviations below the 4,000-year mean. Most recently, grain size over the past 150 years has generally remained above average.

The Pine Lake sediment record thus convincingly identifies the non-CO₂-induced millennial-scale climate oscillation that brings several-century-long periods of alternating dryness and wetness to the southern Alberta region of North America, during concomitant periods of relative hemispheric warmth and coolness, respectively. It also demonstrates there is nothing unusual about the region's current moisture status, which suggests the planet may still have a bit of warming to do before the Current Warm Period is fully upon us.

Laird *et al.* (2003) studied diatom assemblages in sediment cores taken from three Canadian and three United States lakes situated within the northern prairies of North America. For five of the lakes, diatom-inferred salinity estimates were used to reconstruct relative changes in effective moisture (E/P), where E is evaporation and P is precipitation, with high salinity implying high E/P. For the sixth lake, diatom-inferred total phosphorus was used, and chronologies were based on ²¹⁰Pb dating of recent sediments and radiocarbon dates for older sediments.

The seven scientists note their data show “shifts in drought conditions on decadal through multicentennial scales have prevailed in this region for at least the last two millennia.” In Canada, major shifts occurred near the beginning of the Medieval Warm Period, and in the United States they occurred near its end. The scientists state, “distinct patterns of abrupt change in the Northern Hemisphere are common at or near the termination of the Medieval Warm Period (*ca.* A.D. 800–1300) and the onset of the Little Ice Age (*ca.* A.D. 1300–1850).” They also note “millennial-scale shifts over at least the past 5,500 years, between sustained periods of wetter and drier conditions, occurring approximately every 1,220 years, have been reported from western Canada (Cumming *et al.*, 2002),” and “the striking correspondence of these shifts to large changes in fire frequencies, inferred from two sites several hundreds of kilometers to the southwest in the mountain hemlock zone of southern British Columbia (Hallett *et al.*, 2003), suggests that these millennial-scale

dynamics are linked and operate over wide spatial scales.”

Lassen *et al.* (2004) point out “the Norse, under Eric the Red, were able to colonize South Greenland at AD 985, according to the Icelandic Sagas, owing to the mild Medieval Warm Period climate with favorable open-ocean conditions.” They also mention the arrival of the Norsemen was “close to the peak of Medieval warming recorded in the GISP2 ice core which was dated at AD 975 (Stuiver *et al.*, 1995),” and Esper *et al.* (2002) independently identified the peak warmth of this period throughout North American extratropical latitudes as “occurring around 990.” It would appear the window of climatic opportunity provided by the peak warmth of the Medieval Warm Period was a major factor enabling seafaring Scandinavians to establish stable settlements on the coast of Greenland.

As time progressed, however, the glowing promise of the apex of Medieval warmth gave way to the debilitating reality of the depth of Little Ice Age cold. Jensen *et al.* (2004), for example, report the diatom record of Igaliku Fjord “yields evidence of a relatively moist and warm climate at the beginning of settlement, which was crucial for Norse land use,” but “a regime of more extreme climatic fluctuations began soon after AD 1000, and after AD c. 1350 cooling became more severe.” Lassen *et al.* additionally note, “historical documents on Iceland report the presence of the Norse in South Greenland for the last time in AD 1408,” during what they describe as a period of “unprecedented influx of (ice-loaded) East Greenland Current water masses into the innermost parts of Igaliku Fjord.” They also report “studies of a Canadian high-Arctic ice core and nearby geothermal data (Koerner and Fisher, 1990) correspondingly showed a significant temperature lowering at AD 1350–1400,” when, they write, “the Norse society in Greenland was declining and reaching its final stage probably before the end of the fifteenth century.”

Many more details of this incredible saga of five centuries of Nordic survival at the foot of the Greenland Ice Cap also have come to light. Based on a high-resolution record of the fjord's subsurface water-mass properties derived from analyses of benthic foraminifera, Lassen *et al.* conclude stratification of the water column, with Atlantic water masses in its lower reaches, appears to have prevailed throughout the last 3,200 years, except for the Medieval Warm Period. During that period, which they describe as occurring between AD 885 and 1235,

Observations: Temperature Records

the outer part of Igaliku Fjord experienced enhanced vertical mixing (which they attribute to increased wind stress) that would have been expected to increase nutrient availability there. A similar conclusion was reached by Roncaglia and Kuijpers (2004), who found evidence of increased bottom-water ventilation between AD 960 and 1285.

Based on these findings, plus evidence of the presence of *Melonis barleeanus* during the Medieval Warm Period (the distribution of which is mainly controlled by the presence of partly decomposed organic matter), Lassen *et al.* conclude surface productivity in the fjord during this interval of unusual relative warmth was “high and thus could have provided a good supply of marine food for the Norse people.”

Shortly thereafter, the cooling that led to the Little Ice Age was accompanied by a gradual re-stratification of the water column, which curtailed nutrient upwelling and the high level of marine productivity that had prevailed throughout the Medieval Warm Period. These linked events, according to Lassen *et al.*, “contributed to the loss of the Norse settlement in Greenland.” With deteriorating growing conditions on land and simultaneous reductions in oceanic productivity, it was only a matter of time before the Nordic colonies failed. Lassen *et al.* note, “around AD 1450, the climate further deteriorated with further increasing stratification of the water-column associated with stronger advection of (ice-loaded) East Greenland Current water masses.” This led to an even greater “increase of the ice season and a decrease of primary production and marine food supply,” which “could also have had a dramatic influence on the local seal population and thus the feeding basis for the Norse population.”

Lassen *et al.* conclude “climatic and hydrographic changes in the area of the Eastern Settlement were significant in the crucial period when the Norse disappeared.” Also, Jensen *et al.* report, “geomorphological studies in Northeast Greenland have shown evidence of increased winter wind speed, particularly in the period between AD 1420 and 1580 (Christiansen, 1998),” noting “this climatic deterioration coincides with reports of increased sea-ice conditions that caused difficulties in using the old sailing routes from Iceland westbound and further southward along the east coast of Greenland, forcing sailing on more southerly routes when going to Greenland (Seaver, 1996).”

Jensen *et al.* conclude, “life conditions certainly

became harsher during the 500 years of Norse colonization,” and this severe cooling-induced environmental deterioration “may very likely have hastened the disappearance of the culture.” It is also clear the more favorable living conditions associated with the peak warmth of the Medieval Warm Period—which occurred between approximately AD 975 (Stuiver *et al.*, 1995) and AD 990 (Esper *et al.*, 2002)—were what originally enabled the Norse to colonize the region. In the thousand-plus subsequent years, there has never been a sustained period of comparable warmth, nor of comparable terrestrial or marine productivity, either locally or hemispherically (and likely globally, as well).

D’Arrigo *et al.* (2004) sampled trees of white spruce (*Picea glauca* (Moench) Voss) from 14 sites near the elevational treeline on the eastern Seward Peninsula of Alaska, obtaining 46 cores from 38 trees, which they used to develop a maximum latewood density (MXD) chronology for the period AD 1389 to 2001. Calibrating a portion of the latter part of this record (1909–1950) against May–August monthly temperatures obtained from the Nome meteorological station, they converted the entire MXD chronology to warm-season temperatures. This process revealed, they write, “the middle-20th century warming is the warmest 20-year interval since 1640.” Their plot of reconstructed temperatures, however, clearly shows a nearly equivalent warm period near the end of the 1600s, as well as a two-decade period of close-to-similar warmth in the mid-1500s. In the latter part of the 1400s there is a decade warmer than that of the mid-twentieth century. This temperature reconstruction, which the five researchers described as “one of the longest density-based records for northern latitudes,” thus provides yet another indication twentieth century warmth was by no means unprecedented in the past millennium or two, contrary to the claims of Mann *et al.* (1998, 1999) and Mann and Jones (2003). The study instead supports the findings of Esper *et al.* (2002, 2003), McIntyre and McKittrick (2003), and Loehle (2004), which indicate there were several periods over the past millennium or more when it was as warm as, or even warmer than, it was during the twentieth century.

Luckman and Wilson (2005) used new tree-ring data from the Columbia Icefield area of the Canadian Rockies to present a significant update to a millennial temperature reconstruction published for this region in 1997. The update employed different standardization techniques, such as the regional curve standardization method, to capture a greater degree of

low frequency variability (centennial to millennial scale) than reported in the initial study. In addition, the new dataset added more than one hundred years to the chronology that now covers the period 950–1994.

The new tree-ring record was found to explain 53 percent of May–August maximum temperature variation observed in the 1895–1994 data and was thus viewed as a proxy indicator of such temperatures over the past millennium. Based on this relationship, the record showed considerable decadal- and centennial-scale variability, where generally warmer conditions prevailed during the eleventh and twelfth centuries, between about 1350–1450, and from about 1875 through the end of the record. The warmest reconstructed summer occurred in 1434 and was 0.23°C warmer than the next warmest summer, which occurred in 1967, and persistent cold conditions prevailed in 1200–1350, 1450–1550, and 1650–1850, with the 1690s being exceptionally cold (more than 0.4°C colder than other intervals).

The revised Columbia Icefield temperature reconstruction provides further evidence for natural climate fluctuations on centennial-to-millennial time scales and, according to Luckman and Wilson, “appears to indicate a reasonable response of local trees to large-scale forcing of climates, with reconstructed cool conditions comparing well with periods of known low solar activity.”

D’Arrigo *et al.* (2005) used a new tree-ring width dataset derived from 14 white spruce chronologies obtained from the Seward Peninsula, Alaska, covering the years 1358–2001, combined with additional tree-ring width chronologies from northwest Alaska, to produce two versions of a much longer data series that extended to AD 978. The first chronology was created using traditional methods of standardization (STD), which do not perform well in capturing multidecadal or longer climate cycles, while the second chronology utilized the regional curve standardization (RCS) method, which better preserves low-frequency variations at multidecadal time scales and longer. The new, improved, and extended final temperature history of this study provided further evidence for natural climate fluctuations on centennial-to-millennial time scales, capturing the temperature oscillations that produced the Medieval Warm Period (eleventh–thirteenth centuries) and Little Ice Age (1500–1700).

Hallett and Hills (2006) reconstructed the Holocene environmental history of Kootenay Valley in the southern Canadian Rockies based on data obtained from the sediments of Dog Lake, British

Columbia (50°46’N, 116°06’W). They found in the centuries leading up to AD 800, the area had developed “a more open landscape,” and “fire frequencies and summer drought appear to increase,” concluding this increased fire activity was “supported by higher dry-open/wet-closed [forest] pollen ratios and indicates a return to dry-open forest conditions around Dog Lake,” which lasted about 400 years. Thereafter, they found, “wet-closed forest cover reaches its maximum extent from 700–150 cal years BP [AD 1250–1800]” in what “appears to be a response to Little Ice Age cooling.” Finally, they state, “current global warming trends ... may again create the conditions necessary for dry-open ... forest to expand in the Kootenay Valley.” The authors say current global warming may recreate climatic conditions similar to those that prevailed in the Kootenay Valley prior to the global chill of the Little Ice Age, which suggests it has not been as warm there yet, nor for as long a time, as it was between AD 800 and 1200.

Loso *et al.* (2006) presented “a varve thickness chronology from glacier-dammed Iceberg Lake [60°46’N, 142°57’W] in the southern Alaska icefields,” where “radiogenic evidence confirms that laminations are annual and record continuous sediment deposition from AD 442 to AD 1998” and where “varve thickness increases in warm summers because of higher melt, runoff, and sediment transport.” They report the temperatures implied by the varve chronology “were lowest around AD 600, warm between AD 1000 and AD 1300 [which they called “a clear manifestation of the Medieval Warm Period”], cooler between AD 1500 and AD 1850, and have increased dramatically since then.”

The four scientists state their varve record “suggests that 20th century warming is more intense ... than the Medieval Warm Period or any other time in the last 1500 years.” Their graphical representation of varve thickness suggests the intense warming of the twentieth century peaked around 1965 to 1970, after which it was followed by equally intense cooling, such that by 1998, temperatures are implied to have been less than they were during the Medieval Warm Period. The same story is told by tree ring-width anomalies from the adjacent Wrangell Mountains of Alaska, which Loso *et al.* portray as updated from Davi *et al.* (2003). These two databases show the region’s current temperature is lower than it was during the warmest part of the Medieval Warm Period.

Hay *et al.* (2007) analyzed the vertical

Observations: Temperature Records

distributions of diatoms, silicoflagellates, and biogenic silica found in two sediment cores recovered from the inner and outer basins (49°04'N, 125°09'W and 49°02'N, 125°09'W, respectively) of Effingham Inlet, British Columbia, Canada, finding evidence that “a period of warmer and drier climate conditions and possibly increased coastal upwelling offshore occurred ca. 1450–1050 calendar years before present”; i.e., about AD 500–900. Noting “the patterns observed in the diatom record of Effingham Inlet are consistent with regional marine and terrestrial paleoenvironmental records,” they report, “coast range glaciers ... showed a hiatus from 1500 to 1100 calendar years before present,” and this “period of more productive conditions ... was correlative with increased regional primary and marine fish production.” In addition, their data indicated concentrations of *Skeletonema costatum*, which they say “is limited by low temperatures,” were much greater over the AD 550–950 period (which appears to represent the Medieval Warm Period in this part of the world) than in any portion of the following (most recent) millennium.

Zabenskie and Gajewski (2007) extracted sediment cores from Lake JR01 (69°54'N, 95°4.2'W) on the Boothia Peninsula, Nunavut, Canada using a 5-cm diameter Livinstone corer. They note “the uppermost part of the sediment was sampled in a plastic tube with piston to ensure that the sediment-water interface was collected,” and “the upper 20 cm of sediment were sub-sampled into plastic bags at 0.5-cm intervals.” From the fossil pollen assemblages thereby derived, July temperatures were estimated “using the modern analog technique,” as per Sawada (2006). As illustrated in Figure 4.2.4.7.1.1, the two researchers report “maximum estimated July temperatures were reached between 5800 and 3000 cal yr BP, at which time they exceeded present-day values.” Thereafter, temperatures decreased, but with a subsequent “short warming,” which they say “could be interpreted as the Medieval Warm Period,” which they identify as occurring “between 900 and 750 cal yr BP.” After that period of warmth, “temperatures cooled during the Little Ice Age,” as pollen percentages “returned to their values before the [MWP] warming.” During the last 150 years of the record, they observe a “diverse and productive diatom flora,” although “July temperatures reconstructed using the modern analog technique remained stable during this time,” which suggests the Lake JR01 region of the Boothia Peninsula is currently not as warm as it was during the MWP.

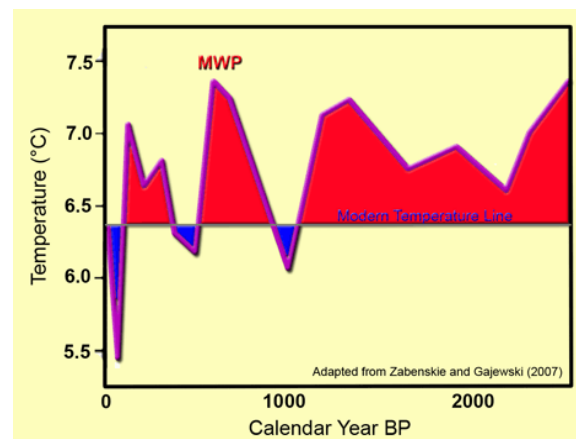


Figure 4.2.4.7.1.1. Reconstructed July mean temperature on the Boothia Peninsula, Nunavut, Canada. Adapted from Zabenskie, S. and Gajewski, K. 2007. Post-glacial climatic change on Boothia Peninsula, Nunavut, Canada. *Quaternary Research* **68**: 261–270.

Podritske and Gajewski (2007) evaluated the relationship between diatoms and temperature by comparing a diatom stratigraphy based on high-resolution sampling with independent paleoclimatic records. They used a high-resolution diatom sequence of the past 9,900 years developed from sediment-core data acquired from a small lake (unofficially named KR02) on Canada’s Victoria Island (located at 71.34°N, 113.78°W) to place recent climatic changes there “in an historical context.” The two researchers report “there is evidence of diatom community response to centennial-scale variations such as the ‘Medieval Warm Period’ (~1000–700 cal yr BP), ‘Little Ice Age’ (~800–150 cal yr BP) and recent warming.” They report the recent warming-induced changes “are not exceptional when placed in the context of diatom community changes over the entire Holocene,” stating, “although recent changes in diatom community composition, productivity, and species richness are apparent, they were surpassed at other periods throughout the Holocene.” The researchers explicitly state the most recent rate of change “was exceeded during the Medieval Warm Period.”

Wiles *et al.* (2008) used “comparisons of temperature sensitive climate proxy records with tree-ring, lichen and radiocarbon dated histories from land-terminating, non-surging glaciers for the last two millennia from southern Alaska” to “identify summer temperature as a primary driver of glacial expansions,” based on “field and laboratory work

over the past decade” that yielded “five new or updated glacier histories,” one each for Bear Glacier (Kenai Mountains), Marathon Mountain Cirque (Kenai Mountains), Amherst Glacier (Chugach Mountains), Crescent Glacier (Chugach Mountains), and Yakutat Glacier (St. Elias Mountains), all located just above the Gulf of Alaska (about 60°N) between approximately 140 to 150°W.

The four researchers’ findings suggest the presence of the Roman Warm Period near the beginning of their 2,000-year record, because of detected “general glacier expansions during the First Millennium AD” that experienced their “strongest advance” at AD 600. The latter cold interval—with ice extent “as extensive as [the] subsequent Little Ice Age”—is typically known as the Dark Ages Cold Period. This cold interval was followed by the Medieval Warm Period (MWP), the evidence for which consisted of “soil formation and forest growth on many forefields in areas that today are only just emerging from beneath retreating termini,” which suggests the MWP was likely both warmer and longer-lived than what has been experienced so far in the Current Warm Period. They also report, “tree-ring chronologies [at the Sheridan, Tebenkof, and Princeton glaciers] show that forest growth on these forefields was continuous between the 900s and 1200s.”

Noting the alternating warm-cold-warm-cold-warm sequence of the past 2,000 years “is consistent with millennial-scale records of ice-rafted debris flux in the North Atlantic and Northern Hemisphere temperature reconstructions,” and “variable Holocene solar irradiance has been proposed as a potential forcing mechanism for millennial-scale climate change,” they conclude “this is supported by the Southern Alaskan glacial record.”

Besonen *et al.* (2008) derived thousand-year histories of varve thickness and sedimentation accumulation rate for Canada’s Lower Murray Lake (81°20’N, 69°30’W), which is typically covered for about 11 months of each year by ice that reaches a thickness of 1.5 to 2 meters at the end of each winter. They note, “field-work on other High Arctic lakes clearly indicates sediment transport and varve thickness are related to temperatures during the short summer season that prevails in this region, and we have no reason to think that this is not the case for Lower Murray Lake.” The six scientists report the varve thickness and sediment accumulation rate histories of Lower Murray Lake show “the twelfth and thirteenth centuries were relatively warm.” Their

data indicate Lower Murray Lake and its environs were often much warmer during this time period (AD 1080–1320) than at any point in the twentieth century, which also has been shown to be the case for Donard Lake (66.25°N, 62°W) by Moore *et al.* (2001).

Payette *et al.* (2008) developed a long-term, spatially explicit fire history of northern boreal forest-tundra in the Riviere Boniface watershed in northeastern Canada (57°45’N, 76°W) based on several years of field investigations designed to exhaustively map and accurately date the occurrences of all fires per each 100-year interval over the last 2,000 years within a 40-km² area in that region. They found there was a “70% reduction of forest cover since 1800 yr BP and nearly complete cessation of forest regeneration since 900 yr BP,” such that “the northern part of the forest tundra in Eastern Canada has been heavily deforested over the last millennium.” They also note “the climate at the tree line was drier and warmer before 900 cal. yr BP.”

The three Canadian researchers conclude the chief direct cause of the post-900 yr BP deforestation was “climate deterioration coinciding with the phasing-out of the Medieval Warmth and incidence of the Little Ice Age.” In addition, since “the latitudinal position of successful post-fire regeneration of lichen-spruce woodlands is situated approximately 1.5° south of the Boniface area, as a rule of thumb it is probable that a drop of at least 1°C in mean annual temperature occurred after 900 cal. yr BP,” they conclude. “Recovery of the boreal forest after a long period of deforestation will require sustained warming,” they state, which they add has been occurring only “since the mid-1990s in Eastern subarctic Canada.”

Edwards *et al.* (2008) developed a cellulose $\delta^{13}\text{C}$ dendrochronology “from cross-dated 10-year increments of 16 sub-fossil snags and living-tree ring sequences of *Picea engelmannii* (Englemann spruce) from upper alpine treeline sites near Athabasca Glacier and subfossil material from the forefield of Robson Glacier plus living and snag material of *Pinus albicaulis* (whitebark pine) adjacent to Bennington Glacier, spanning AD 951–1990,” as well as from an oxygen isotope ($\delta^{18}\text{O}$) dendro-chronology for the same period. They calculated past changes in relative humidity and temperature over Canada’s Columbia Icefield in the general vicinity of 53°N, 118°W. They report several “intriguing new discoveries,” one of which is “evidence of previously unrecognized winter warmth during the Medieval Climate Anomaly (~AD 1100–1250),” as illustrated in Figure 4.2.4.7.1.2.

Observations: Temperature Records

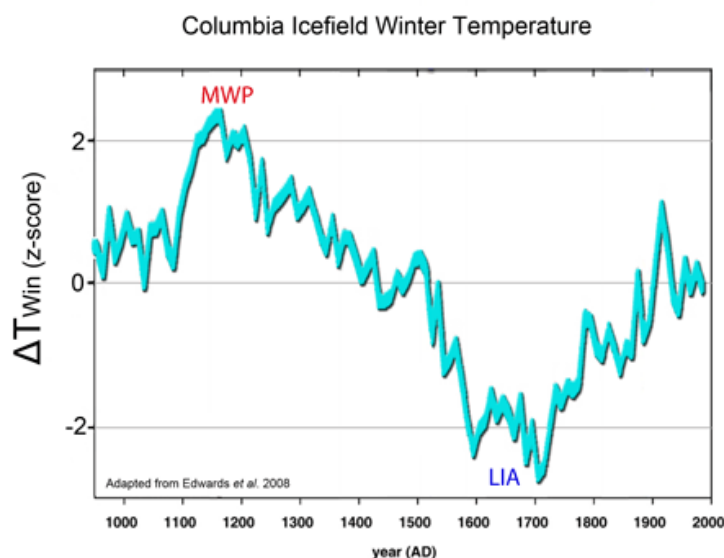


Figure 4.2.4.7.1.2. Columbia Icefield mean winter temperature z-scores relative to that of the period AD 1941–1990. Adapted from Edwards, T.W.D., Birks, S.J., Luckman, B.H., and MacDonald, G.M. 2008. Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada. *Quaternary Research* 70: 188–197.

The four researchers' results show the peak winter temperature of the Medieval Climate Anomaly throughout Canada's Columbia Icefield was warmer than the peak temperature of the Current Warm Period (which appears to have occurred ~1915), and it was even warmer than the mean temperature of the 1941–1990 base period as well as the mean temperature of the last ten years of that period (1980–1990).

Barclay *et al.* (2009) note “tree-ring crossdates of glacially killed logs have provided a precisely dated and detailed picture of Little Ice Age (LIA) glacier fluctuations in southern Alaska,” and they extended this history into the First Millennium AD (FMA) by integrating similar data obtained from additional log collections made in 1999 with the prior data to produce a new history of advances and retreats of the Tebenkof Glacier spanning the past two millennia.

Figure 4.2.4.7.1.3 shows between the FMA and LIA extensions of the Tebenkof Glacier terminus, there was a period between about AD 950 and 1230 when the terminus

dropped further than two kilometers back from the maximum LIA extension that occurred near the end of the nineteenth century. This warmer/drier period of glacier terminus retreat had to have been much more extreme than what was experienced at any time during the twentieth century, because at the century's end the glacier's terminus had not yet retreated more than two kilometers back from the line of its maximum LIA extension. This 280-year period of likely greater warmth and dryness falls in the middle of the broad peak of maximum warmth during the global Medieval Warm Period.

Based on the data depicted in Figure 4.2.4.7.1.3, it would appear the central portion of the Medieval Warm Period in southern Alaska was likely significantly warmer and drier than at any time during the twentieth century. It can be further concluded there is nothing unprecedented or unusual about that region's current warmth and dryness, which means there is no need to invoke anthropogenic CO₂ emissions as a cause.

Rolland *et al.* (2009) reconstructed the late-Holocene evolution of a Southampton Island lake known as Tasiq Qikitalik (65°05'70"N, 83°47'49"W)

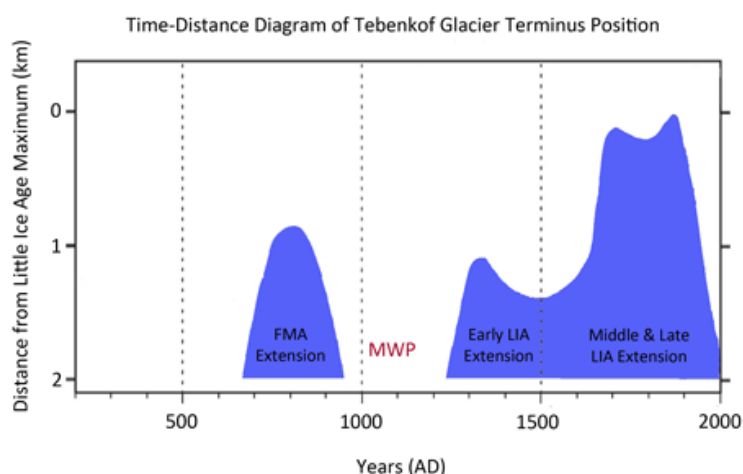


Figure 4.2.4.7.1.3. The temporal history of the distance by which the terminus of the Tebenkof Glacier fell short of its maximum LIA extension over the past two millennia. Adapted from Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Tree-ring crossdates for a first millennium AD advance of Tebenkof Glacier, southern Alaska. *Quaternary Research* 71: 22–26.

in Nunavut, Canada by studying fossil chironomid distributions along with sedimentological data (X-ray fluorescence, grain size, and C/N ratios) obtained from a sediment core retrieved from the lake's deepest reachable point, deriving in the process a 1,200-year history of inferred August temperatures. They discovered “higher temperatures were recorded from cal yr AD 1160 to AD 1360, which may correspond to the Medieval Warm Period,” and “between cal yr AD 1360 and AD 1700, lower temperatures were probably related to a Little Ice Age event,” with the latter period exhibiting a minimum August temperature “ca. 2°C colder than the maximum observed during the Medieval Warm Period.” The most recent August temperature, which occurred at the end of the record at about 2008, is approximately 0.9°C less than the maximum August temperature of the Medieval Warm Period.

Laird and Cumming (2009) developed a history of changes in the level of Lake 259 (Rawson Lake, 49°40'N, 93°44'W) within the Experimental Lakes Area of northwestern Ontario, Canada based on a suite of near-shore gravity cores they analyzed for diatom species identity and concentration, as well as organic matter content. They discovered “a distinct decline in lake level of ~2.5 to 3.0 m from ~800 to 1130 AD.” This interval, they write, “corresponds to an epic drought recorded in many regions of North America from ~800 to 1400 AD,” which they say was “often referred to as the Medieval Climatic Anomaly or the Medieval Warm Period,” and which also “encompasses ‘The Great Drought’ of the thirteenth century (Woodhouse and Overpeck, 1998; Woodhouse, 2004; Herweijer *et al.* 2007).” They note the Canadian prairies were at that time “experiencing reductions in surface-water availability due to climate warming and human withdrawals (Schindler and Donahue, 2006),” and many regions in the western U.S. had experienced water supply deficits in reservoir storage with the multi-year drought described by Cook *et al.* (2007). They report “these severe multi-year drought conditions pale in comparison to the many widespread megadroughts that persisted for decades and sometimes centuries in many parts of North America over the last millennium (Woodhouse, 2004).”

Clegg *et al.* (2010) conducted a high-resolution analysis of midge assemblages found in the sediments of Moose Lake (61°22.45'N, 143°35.93'W) in the Wrangell-St. Elias National Park and Preserve of south-central Alaska, based on data obtained from cores removed from the lake bottom in summer 2000

and a midge-to-temperature transfer function that yielded mean July temperatures (T_{July}) for the past six thousand years. Some of the results of this study are portrayed in Figure 4.2.4.7.1.4, which shows, from about 2,600 cal yr BP to the present, a clear multi-centennial oscillation about the declining trend, with peaks and valleys defining the temporal locations of the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and the start of the Current Warm Period, which is still not expressed to any significant degree compared to the Medieval and Roman Warm Periods.

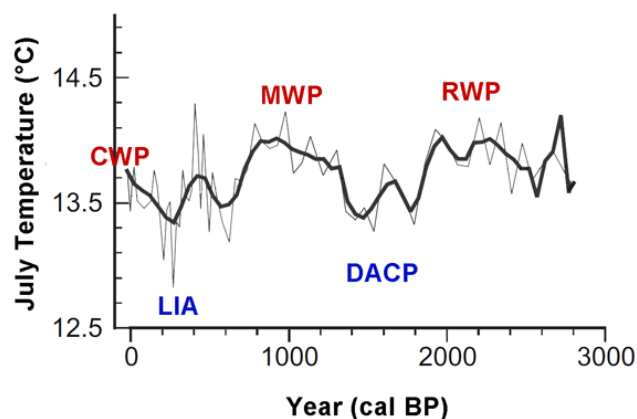


Figure 4.2.4.7.1.4. Mean July near-surface temperature (°C) vs. years before present (cal BP) for south-central Alaska (USA). Adapted from Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tinner, W., and Hu, F.S. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. *Quaternary Science Reviews* 29: 3308–3316.

The seven scientists write, “comparisons of the T_{July} record from Moose Lake with other Alaskan temperature records suggest that the regional coherency observed in instrumental temperature records (e.g., Wiles *et al.*, 1998; Gedalof and Smith, 2001; Wilson *et al.*, 2007) extends broadly to at least 2000 cal BP.” In addition, they note climatic events such as the LIA and the MWP occurred “largely synchronously” between their T_{July} record from Moose Lake and a $\delta^{18}\text{O}$ -based temperature record from Farewell Lake on the northwestern foothills of the Alaska Range, and “local temperature minima likely associated with First Millennium AD Cooling (centered at 1400 cal BP; Wiles *et al.*, 2008) are evident at both Farewell and Hallet lakes (McKay *et al.*, 2008).”

Observations: Temperature Records

Wolfe *et al.* (2011) note the level of Canada's Lake Athabasca—North America's ninth-largest lake, located in the northwest corner of Saskatchewan and the northeast corner of Alberta between 58° and 60° N—"is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains (Wolfe *et al.*, 2008; Johnston *et al.*, 2010; Sinnatamby *et al.*, 2010)." In addition, they write, "paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks (Wolfe *et al.*, 2008)." They also note "the highest levels of the last 1000 years occurred c. 1600–1900 CE [=AD] during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies," and the "lowest levels existed at c. 970–1080 CE at a time of low glacier volume," near the midpoint of the global Medieval Warm Period.

In their newest study of the subject, the four Canadian researchers expanded the time span of the lake-level history to the past 5,200 years, based on new analyses of sediment cores they collected in July 2004 from North Pond (a lagoon on Bustard Island located at the western end of Lake Athabasca). They discovered (see Figure 4.2.4.7.1.5) "modern society in western Canada developed during a rare interval of relatively abundant freshwater supply—now a rapidly diminishing by-product of the LIA glacier expansion, which is in agreement with late 20th century decline in Athabasca River discharge identified in hydrometric records (Burn *et al.*, 2004; Schindler and Donahue, 2006)." In addition, their data suggest "the transition from water abundance to scarcity can occur within a human lifespan," which, as they caution, "is a very short amount of time for societies to adapt."

Their data suggest the peak warmth of the

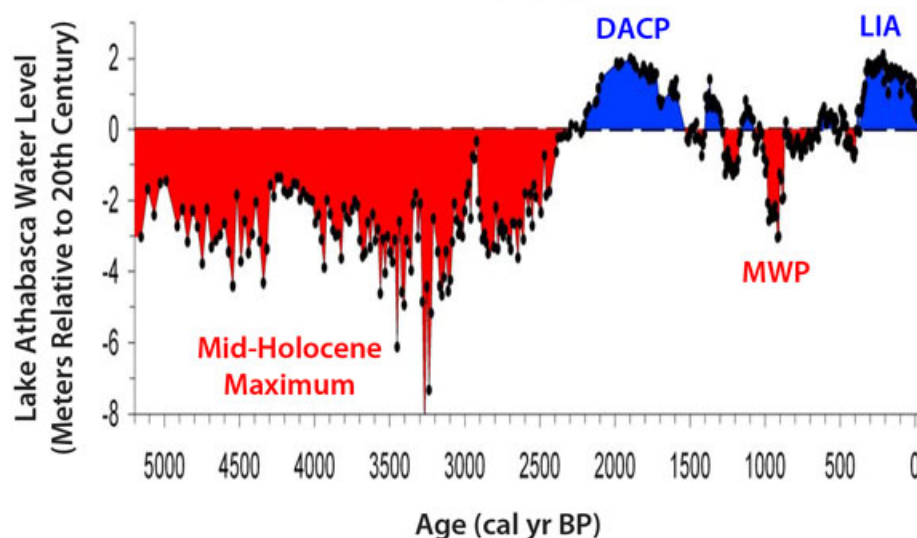


Figure 4.2.4.7.1.5. The Reconstructed water level history of Lake Athabasca. Adapted from Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.

Medieval Warm Period was likely significantly greater than the peak warmth experienced to date during the Current Warm Period. The rapidly declining water level over the past couple of decades—when Earth's temperature was near its modern peak but exhibited very little trend—suggests lake level could continue its rapid downward course if planetary temperatures merely maintain their current values. Wolfe *et al.* conclude, "as consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory."

Galloway *et al.* (2011) studied an 11.6-m sediment core they extracted in June 2001 from the deepest point of Felker Lake (51°57.0'N, 121°59.9'W), which sits in the rain shadow generated by Canada's Coast, Cascade, and Columbia Mountains. They analyzed diatom assemblages, together with pollen and spore types and quantities, to produce an 11,670-year record of hydrological change throughout the Holocene, based on a calibration dataset of 219 lakes from British Columbia, including Felker Lake, and select lakes from the Northern Great Plains (Wilson *et al.*, 1996). This work provided evidence for what they call a "millennial-scale pacing of climate" throughout the Holocene. They report

Climate Change Reconsidered II

“the most extreme episode of hydrological change occurred from ca. 1030 cal. year BP to ca. 690 cal. year BP,” a period they note was “broadly coeval with the Medieval Warm Period.” They say “a coeval warm and dry interval is recognized in numerous paleoclimate studies in western North America,” citing the work of Hallett *et al.* (2003), Laird *et al.* (2003), and Bracht *et al.* (2007).

That the warm and dry interval Galloway *et al.* discovered at Felker Lake during the heart of the Medieval Warm Period was the most extreme such period of the entire Holocene indicates just how unusual the Medieval Warm Period was in this regard ... and further reveals the *non-uniqueness* of the warmth and dryness experienced in that part of the world during the establishment of the planet’s Current Warm Period.

Kobashi *et al.* (2011) write, “Greenland recently incurred record high temperatures and ice loss by melting, adding to concerns that anthropogenic warming is impacting the Greenland ice sheet and in turn accelerating global sea-level rise.” They also note “it remains imprecisely known for Greenland how much warming is caused by increasing atmospheric greenhouse gases versus natural variability.” They reconstructed Greenland surface snow temperature variability over the past 4,000 years at the GISP2 site (near the Summit of the Greenland ice sheet; hereafter referred to as Greenland temperature) with a new method that utilizes argon and nitrogen isotopic ratios from occluded air bubbles, as described in detail by Kobashi *et al.* (2008a,b).

The eight researchers report “the temperature record starts with a colder period in ‘the Bronze Age Cold Epoch,’” which they say was followed by “a warm period in ‘the Bronze Age Optimum,’” after which there was a 1,000-year cooling that began “during ‘the Iron/Roman Age Optimum,’” followed by “the Dark Ages.” That period was followed by

“the Medieval Warm Period,” after which occurred “the Little Ice Age, which they describe as “the coldest period of the past 4000 years,” which was followed, finally, by “the recent warming.” They note “the current decadal average surface temperature at the summit is as warm as in the 1930s–1940s, and there was another similarly warm period in the 1140s (Medieval Warm Period),” indicating “the present decade is not outside the envelope of variability of the last 1000 years.” They write, “excluding the last millennium,” there were fully “72 decades warmer than the present one, in which mean temperatures were 1.0 to 1.5°C warmer,” and during two centennial intervals, average temperatures “were nearly 1.0°C warmer than the present decade” (see Figure 4.2.4.7.1.6).

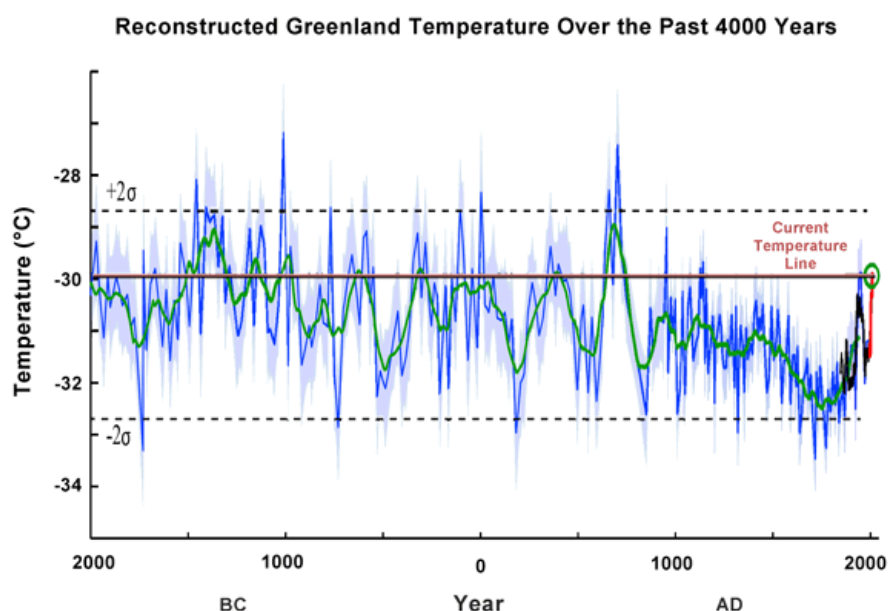


Figure 4.2.4.7.1.6. Reconstructed Greenland snow surface temperatures for the past 4,000 years. The blue line and blue band represent the reconstructed Greenland temperature and 1σ error, respectively. The green line represents a 100-year moving average of the blue line. The black and red lines indicate the Summit and AWS decadal average temperatures, respectively, as calculated by others. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: 10.1029/2011GL049444.

Since the Greenland summit’s decadal warmth of the first ten years of the twenty-first century was exceeded fully six dozen times over the prior four millennia, it clearly was in no way unusual, and

Observations: Temperature Records

therefore it is also clear none of Greenland's recent warming has necessarily been caused by increasing concentrations of greenhouse gases. It is far more likely its recent warmth is the next expected phase of the natural oscillation of climate that has produced numerous multi-century periods of alternating warmth and cold over the past four thousand years.

Bunbury and Gajewski (2012) obtained sediment cores from two lakes in the interior southwest of Canada's Yukon Territory—Jenny Lake (61.04°N, 138.36°W) and Upper Fly Lake (61.04°N, 138.09°W)—which, they write, “yielded chironomid records that were used to provide quantitative estimates of mean July air temperature.” The two researchers report their chironomid-inferred temperature estimates from the two lakes “compare well with one another and also with other paleoclimate evidence from the region,” noting their data suggest “relatively warm conditions during medieval times, centered on AD 1200, followed by a cool Little Ice Age, and warming temperatures over the past 100 years.” It can be estimated from the graphical representations of their data that the Medieval Warm Period at both lake sites extended from about AD 1100 to 1350, and it also can be estimated that the most recent (AD 1990) of their temperature determinations were about 0.8°C cooler than the peak warmth of the Medieval Warm Period at Jenny Lake and approximately 0.5°C cooler at Upper Fly Lake.

References

- Arseneault, D. and Payette, S. 1997. Reconstruction of millennial forest dynamics from tree remains in a subarctic tree line peatland. *Ecology* **78**: 1873–1883.
- Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Tree-ring crossdates for a first millennium AD advance of Tebenkof Glacier, southern Alaska. *Quaternary Research* **71**: 22–26.
- Besonen, M.R., Patridge, W., Bradley, R.S., Francus, P., Stoner, J.S., and Abbott, M.B. 2008. A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic. *The Holocene* **18**: 169–180.
- Bracht, B.B., Stone, J.R., and Fritz, S.C. 2007. A diatom record of late Holocene climate variation in the northern range of Yellowstone National Park, USA. *Quaternary International* **188**: 149–155.
- Bunbury, J. and Gajewski, K. 2012. Temperatures of the past 2000 years inferred from lake sediments, southwest Yukon Territory, Canada. *Quaternary Research* **77**: 355–367.
- Burn, D.H., Abdul Aziz, O.I., and Pictroniro, A. 2004. A comparison of trends in hydrological variables for two watersheds in the Mackenzie River Basin. *Canadian Water Resources Journal* **29**: 283–298.
- Calkin, P.E., Wiles, G.C., and Barclay, D.J. 2001. Holocene coastal glaciation of Alaska. *Quaternary Science Reviews* **20**: 449–461.
- Campbell, C. 2002. Late Holocene lake sedimentology and climate change in southern Alberta, Canada. *Quaternary Research* **49**: 96–101.
- Campbell, I.D. and Campbell, C. 2000. Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**: 279–296.
- Christiansen, H.H. 1998. ‘Little Ice Age’ nivation activity in northeast Greenland. *The Holocene* **8**: 719–728.
- Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tinner, W., and Hu, F.S. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. *Quaternary Science Reviews* **29**: 3308–3316.
- Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American drought: reconstructions, causes, and consequences. *Earth Science Reviews* **81**: 93–134.
- Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2010. Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* **25**: 48–61.
- Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Cumming, B.F., Laird, K.R., Bennett, J.R., Smol, J.P., and Salomon, A.K. 2002. Persistent millennial-scale shifts in moisture regimes in western Canada during the past six millennia. *Proceedings of the National Academy of Sciences USA* **99**: 16,117–16,121.
- D’Arrigo, R., Mashig, E., Frank, D., Jacoby, G., and Wilson, R. 2004. Reconstructed warm season temperatures for Nome, Seward Peninsula, Alaska. *Geophysical Research Letters* **31**: 10.1029/2004GL019756.
- D’Arrigo, R., Mashig, E., Frank, D., Wilson, R., and Jacoby, G. 2005. Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. *Climate Dynamics* **24**: 227–236.
- Davi, N.K., Jacoby, G.C., and Wiles, G.C. 2003. Boreal

Climate Change Reconsidered II

temperature variability inferred from maximum latewood density and tree-ring width data, Wrangell Mountain region, Alaska. *Quaternary Research* **60**: 252–262.

Edwards, T.W.D., Birks, S.J., Luckman, B.H., and MacDonald, G.M. 2008. Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada. *Quaternary Research* **70**: 188–197.

Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.

Esper, J., Shiyatov, S.G., Mazepa, V.S., Wilson, R.J.S., Graybill, D.A., and Funkhouser, G. 2003. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. *Climate Dynamics* **21**: 699–706.

Galloway, J.M., Lenny, A.M., and Cumming, B.F. 2011. Hydrological change in the central interior of British Columbia, Canada: diatom and pollen evidence of millennial-to-centennial scale change over the Holocene. *Journal of Paleolimnology* **45**: 183–197.

Gedalof, Z. and Smith, D.J. 2001. Interdecadal climate variability and regime scale shifts in Pacific North America. *Geophysical Research Letters* **28**: 1515–1518.

Hallett, D.J. and Hills, L.V. 2006. Holocene vegetation dynamics, fire history, lake level and climate change in the Kootenay Valley, southeastern British Columbia, Canada. *Journal of Paleolimnology* **35**: 351–371.

Hallett, D.J., Lepofsky, D.S., Mathewes, R.W., and Lertzman, K.P. 2003a. 11,000 years of fire history and climate in the mountain hemlock rain forests of southwestern British Columbia based on sedimentary charcoal. *Canadian Journal of Forest Research* **33**: 292–312.

Hallett, D.J., Mathewes, R.W., and Walker, R.C. 2003b. A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada. *The Holocene* **13**: 751–761.

Hay, M.B., Dallimore, A., Thomson, R.E., Calvert, S.E., and Pienitz, R. 2007. Siliceous microfossil record of late Holocene oceanography and climate along the west coast of Vancouver Island, British Columbia (Canada). *Quaternary Research* **67**: 33–49.

Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.

Hu, F.S., Ito, E., Brown, T.A., Curry, B.B., and Engstrom, D.R. 2001. Pronounced climatic variations in Alaska

during the last two millennia. *Proceedings of the National Academy of Sciences, USA* **98**: 10,552–10,556.

Jensen, K.G., Kuijpers, A., Koc, N., and Heinemeier, J. 2004. Diatom evidence of hydrographic changes and ice conditions in Igaliku Fjord, South Greenland, during the past 1500 years. *The Holocene* **14**: 152–164.

Johnston, J.W., Koster, D., Wolfe, B.B., Hall, R.I., Edwards, T.W.D., Endres, A.L., Martin, M.E., Wiklund, J.A., and Light, C. 2010. Quantifying Lake Athabasca (Canada) water level during the Little Ice Age highstand from paleolimnological and geophysical analyses of a transgressive barrier-beach complex. *The Holocene* **20**: 801–811.

Kaplan, M.R., Wolfe, A.P., and Miller, G.H. 2002. Holocene environmental variability in southern Greenland inferred from lake sediments. *Quaternary Research* **58**: 149–159.

Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: 10.1029/2011GL049444.

Kobashi, T., Severinghaus, J.P., and Barnola, J.-M. 2008a. $4 \pm 1.5^\circ\text{C}$ abrupt warming 11,270 yr ago identified from trapped air in Greenland ice. *Earth and Planetary Science Letters* **268**: 397–407.

Kobashi, T., Severinghaus, J.P., and Kawamura, K. 2008b. Argon and nitrogen isotopes of trapped air in the GISP2 ice core during the Holocene epoch (0–11,600 B.P.): methodology and implications for gas loss processes. *Geochimica et Cosmochimica Acta* **72**: 4675–4686.

Koerner, R.M. and Fisher, D.A. 1990. A record of Holocene summer climate from a Canadian high-Arctic ice core. *Nature* **343**: 630–631.

Laird, K.R., Cumming, B.F., Wunsam, S., Rusak, J.A., Oglesby, R.J., Fritz, S.C., and Leavitt, P.R. 2003. Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proceedings of the National Academy of Sciences USA* **100**: 2483–2488.

Lassen, S.J., Kuijpers, A., Kunzendorf, H., Hoffmann-Wieck, G., Mikkelsen, N., and Konradi, P. 2004. Late-Holocene Atlantic bottom-water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas. *The Holocene* **14**: 165–171.

Loehle, C. 2004. Climate change: detection and attribution of trends from long-term geologic data. *Ecological Modelling* **171**: 433–450.

Loso, M.G., Anderson, R.S., Anderson, S.P., and Reimer,

Observations: Temperature Records

- P.J. 2006. A 1500-year record of temperature and glacial response inferred from varved Iceberg Lake, southcentral Alaska. *Quaternary Research* **66**: 12–24.
- Luckman, B.H. and Wilson, R.J.S. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics* **24**: 131–144.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.
- McIntyre, S. and McKittrick, R. 2003. Corrections to the Mann *et al.* (1998) proxy data base and Northern Hemispheric average temperature series. *Energy and Environment* **14**: 751–771.
- McKay, N.P., Kaufman, D.S., and Michelutti, N. 2008. Biogenic-silica concentration as a high-resolution, quantitative temperature proxy at Hallet Lake, south-central Alaska. *Geophysical Research Letters* **35**: L05709.
- Moore, J.J., Huguen, K.A., Miller, G.H., and Overpeck, J.T. 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. *Journal of Paleolimnology* **25**: 503–517.
- Payette, S., Filion, L., and Delwaide, A. 2008. Spatially explicit fire-climate history of the boreal forest-tundra (Eastern Canada) over the last 2000 years. *Philosophical Transactions of the Royal Society B* **363**: 2301–2316.
- Podrinkske, B. and Gajewski, K. 2007. Diatom community response to multiple scales of Holocene climate variability in a small lake on Victoria Island, NWT, Canada. *Quaternary Science Reviews* **26**: 3179–3196.
- Rolland, N., Larocque, I., Francus, P., Pienitz, R., and Laperriere, L. 2009. Evidence for a warmer period during the 12th and 13th centuries AD from chironomid assemblages in Southampton Island, Nunavut, Canada. *Quaternary Research* **72**: 27–37.
- Roncaglia, L. and Kuijpers A. 2004. Palynofacies analysis and organic-walled dinoflagellate cysts in late-Holocene sediments from Igaliku Fjord, South Greenland. *The Holocene* **14**: 172–184.
- Routson, C.C., Woodhouse, C.A., and Overpeck, J.T. 2011. Second century megadrought in the Rio Grande headwaters, Colorado: How unusual was medieval drought? *Geophysical Research Letters* **38**: 10.1029/2011GL050015.
- Sawada, M. 2006. An open source implementation of the Modern Analog Technique (MAT) within the R computing environment. *Computers & Geosciences* **32**: 818–833.
- Schindler, D.W. and Donahue, W.F. 2006. An impending water crisis in Canada’s western prairie provinces. *Proceedings of the National Academy of Sciences, USA* **103**: 7210–7216.
- Seaver, K.A. 1996. *The Frozen Echo: Greenland and the Exploration of North America AD c. 1000–1500*. Stanford University Press, Stanford, CA, USA.
- Sinnatamby, R.N., Yi, Y., Sokal, M.A., Clogg-Wright, K.P., Asada, T., Vardy, S.H., Karst-Riddoch, T.L., Last, W.M., Johnston, J.W., Hall, R.I., Wolfe, B.B., and Edwards, T.W.D. 2010. Historical and paleolimnological evidence for expansion of Lake Athabasca (Canada) during the Little Ice Age. *Journal of Paleolimnology* **43**: 705–717.
- Stuiver, M., Grootes, P.M., and Braziunas, T.F. 1995. The GISP2 $\delta^{18}\text{O}$ climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* **44**: 341–354.
- Wiles, G.C., Barclay, D.J., Calkin, P.E., and Lowell, T.V. 2008. Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of Southern Alaska. *Global and Planetary Change* **60**: 115–125.
- Wilson, S.E., Cumming, B.F., and Smol, J.P. 1996. Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219-lake data set from western North America. *Canadian Journal of Fisheries and Aquatic Sciences* **53**: 1580–1594.
- Wilson, R., Wiles, G., D’Arrigo, R., and Zwick, C. 2007. Cycles and shifts: 1300 years of multi-decadal temperature variability in the Gulf of Alaska. *Climate Dynamics* **28**: 425–440.
- Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.
- Wolfe, B.B., Hall, R.I., Edwards, T.W.D., Jarvis, S.R., Sinnatamby, R.N., Yi, Y., and Johnston, J.W. 2008. Climate-driven shifts in quantity and seasonality of river discharge over the past 1000 years from the hydrographic apex of North America. *Geophysical Research Letters* **35**: 10.1029/2008GL036125.
- Woodhouse, C.A. 2004. A paleo-perspective on

hydroclimatic variability in the western United States. *Aquatic Science* **66**: 346–356.

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W., and Cook, E.R. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences USA* **107**: 21,283–21,288.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

Zabenskie, S. and Gajewski, K. 2007. Post-glacial climatic change on Boothia Peninsula, Nunavut, Canada. *Quaternary Research* **68**: 261–270.

4.2.4.7.2 United States

The IPCC claims rising atmospheric CO₂ concentrations due to the burning of fossil fuels such as coal, gas and oil have raised global air temperatures to their highest level in the past one to two millennia. Therefore, investigating the possibility of a period of equal global warmth within the past one to two thousand years has become a high-priority enterprise, for if such a period can be shown to have existed when the atmosphere's CO₂ concentration was far less than it is today, there will be no compelling reason to attribute the warmth of our day to the CO₂ released into the air by mankind since the beginning of the Industrial Revolution. This section reviews studies of this topic conducted within the confines of the lower 48 contiguous states of the United States of America.

Lloyd and Graumlich (1997) derived 3,500-year histories of treeline elevation fluctuation and tree abundance for five sites in the southern Sierra Nevada (~36.5°N, 108.25°W). They found synchronous increases in treeline elevation from AD 800 to 900 and an episode of high tree abundance above the current treeline between AD 700 and 1200, which implies warmer-than-present temperatures during that period.

Ingram *et al.* (1998) conducted isotopic (¹⁸O/¹⁶O and ¹³C/¹²C) and elemental chemical analyses (Sr/Ca and Mg/Ca ratios) of sediment cores taken from Petaluma Marsh, San Francisco Bay, Northern California, to develop a record of paleoenvironmental change in this region over the past 700 years. They report high frequency variations in δ¹⁸O, δ¹³C, Mg/Ca, and Sr/Ca were noted throughout the 700-yr record, indicating the presence of oscillations in freshwater inflow, temperature, and evaporation at

periods of 35–115 years. Between 150 and 400 cal yr BP, δ¹⁸O and Mg/Ca were relatively low, indicating a period of cold and wet climatic conditions associated with the Little Ice Age. Before that, δ¹⁸O and Mg/Ca were higher from 480 to 650 cal yr BP, indicating, in the words of Ingram *et al.*, “drier and warmer conditions during the end of the Medieval Warm Period.” In addition, they note, the record “suggests that the duration of wet and dry periods was greater over the past 700 years than in the twentieth century instrumental record.” Ingram *et al.*'s work supports the findings of Graumlich (1990), who found tree-ring evidence in the nearby Sierra Nevada Mountains that the period from 510 to 420 cal yr BP was warmer and wetter than any part of the twentieth century.

Patterson (1998) obtained seasonal temperature variations from δ¹⁸O(CaCO₃) values of late Holocene sagittal fish otoliths recovered from archaeological sites along the southern and western basin of Lake Erie (~41.5°N, 82.75°W). At the turn of the first millennium AD, “both summer maximum and mean annual temperatures in the Great Lakes region were found to be higher than those of the 20th century,” whereas winter temperatures at that time were lower, Patterson writes. Summer temperatures at AD 985 were 2 to 6°C warmer than those of 1936–1992, and mean annual temperatures were 0.2°C higher and mean winter temperatures 1.8°C lower. Hence, there was probably no significant difference between the mean annual temperature around AD 985 and the mean annual temperature of the 1980s and 1990s.

Hadley *et al.* (1998) examined body size characteristics of pocket gopher (*Thomomys talpoides*) remains obtained from Lamar Cave, Yellowstone National Park (~45°N, 110°W). During the Medieval Warm Period, pocket gophers had a significantly shorter (89 percent of mean value) diastema (the gap between the animals' molars and incisors) and presumably smaller body size than in colder times, the scientists found. This finding, they write, “accords with Bergmann's rule, which states that animals from warmer parts of a geographic range tend to be smaller.” Because modern diastema lengths are not nearly as short as diastema lengths during Medieval times (see Figure 4.2.4.7.2.1), it can be concluded the MWP was likely warmer than the CWP.

Gavin and Brubaker (1999) extracted three 18-cm-deep soil cores from three sites within a subalpine meadow they refer to as Meadow Ridge in Royal Basin (47°49'N, 123°12'30" W), a north-facing glacial valley at the headwaters of Royal Creek in

Observations: Temperature Records

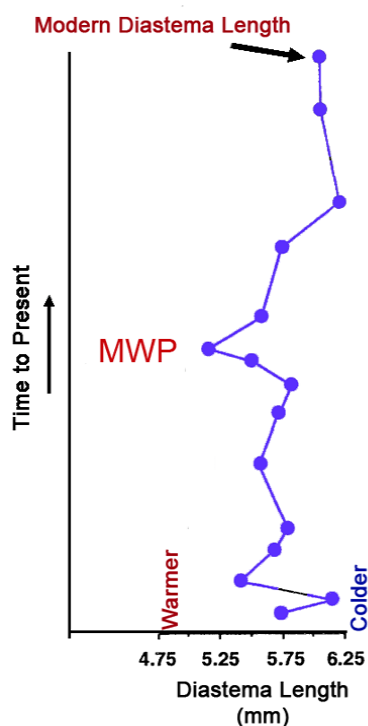


Figure 4.2.4.7.2.1. Diasteme length of pocket gopher remains obtained from Lamar Cave, Yellowstone National Park. Adapted from Hadley, E.A., Kohn, M.H., Leonard, J.A., and Wayne, R.K. 1998. A genetic record of population isolation in pocket gophers during Holocene climatic change. *Proceedings of the National Academy of Sciences, USA* **95**: 6893–6896..

northeastern Olympic National Park in the state of Washington. They constructed depth (= time) profiles of pollen types and abundances over the past six millennia. Based on current associations of the plants that produced the pollen with various climatic parameters, primarily temperature and precipitation, they reconstructed a climatic history of the three sites.

In the part of the soil profiles “corresponding to the Medieval Warm Period (c. 1200–700 BP),” all sites showed an increase in the abundance of *Polygonum bistortoides*, “an indicator of mesic conditions.” At one of the sites, it reached a maximum abundance of 50 percent, which they say is “more than three times the value in any modern surface sample at Meadow Ridge.” In addition, one of the sites showed “a decline in Cyperaceae (cf. *Carex nigricans*),” which “suggests earlier snow-melt dates.” They conclude the observed changes “suggest long and moist growing seasons” during the Medieval Warm Period. In addition, they note the pollen-plant

relationship they developed for *P. bistortoides* over this period “corresponds to c. 75% cover,” which is “higher than any reported *Polygonum bistortoides* cover in the Olympic Mountains (Schreiner, 1994),” suggesting the MWP of AD 800–1300 was very likely significantly warmer than the Current Warm Period in that part of the world has been to date.

Field and Baumgartner (2000) developed “a robust time series of stable isotope [$\delta^{18}\text{O}$ from *Neogloboquadrina dutertrei*] variability over the past millennium from the varved sediments of the Santa Barbara Basin,” which they related to observed environmental variability within this part of the California Current over the past half-century, thereby demonstrating “thermal variability dominates the $\delta^{18}\text{O}$ signal.”

The two researchers report, “an anomalously warm coastal ocean persisted at the multicentennial-scale from roughly AD 1200 to 1450,” and this period, as they describe it, “coincides with the age generally assigned to the ‘Medieval Warm Period.’” They also report “the period of positive anomalies in the low-frequency series of $\delta^{18}\text{O}$ from *N. dutertrei* that continues from ~AD 1450 to ~1800 is consistent with the dates associated with the cooling and neoglaciation of the ‘Little Ice Age’ in both the Southern and Northern Hemispheres.” In addition, they note “the long-term ocean warming and cooling of the California Current region appears to be in phase with the warming and cooling of the midlatitude North Atlantic described by Keigwin (1996).”

Brush (2001) analyzed sediment cores obtained from tributaries, marshes, and the main stem of Chesapeake Bay for paleoecological indicators of regional climate change and land-use variations over the past millennium. They found “the Medieval Climatic Anomaly and the Little Ice Age are recorded in Chesapeake sediments by terrestrial indicators of dry conditions for 200 years, beginning about 1000 years ago, followed by increases in wet indicators from about 800 to 400 years ago.” This MCA is what most people refer to as the Medieval Warm Period (MWP), which Brush says is “recognized in many parts of the world from historical and paleoecological evidence.” The findings of this paper therefore represent additional evidence for the uniqueness of both the Medieval Warm Period and the Little Ice Age, the two preeminent climatic anomalies of the past thousand years, further suggesting there is nothing unusual about the global warming of the past century or so, as it represents the planet’s natural

recovery from the global chill of the Little Ice Age and the start of its return to conditions more like those of the Medieval Warm Period.

Viau *et al.* (2002) analyzed a set of 3,076 ^{14}C dates from the North American Pollen Database used to date sequences in more than 700 pollen diagrams across North America. They found nine millennial-scale oscillations during the past 14,000 years in which continent-wide synchronous vegetation changes with a periodicity of roughly 1,650 years were recorded in the pollen records. The most recent of the vegetation transitions was centered at approximately 600 years BP (before present). This event, they write, culminated “in the Little Ice Age, with maximum cooling 300 years ago.” Before that event, a major transition that began approximately 1,600 years BP represents the climatic amelioration that culminated “in the maximum warming of the Medieval Warm Period 1000 years ago,” they note. And so it goes, back through the Holocene and into the preceding late glacial period, with the times of all major pollen transitions being “consistent with ice and marine records.”

According to the five researchers, “the large-scale nature of these transitions and the fact that they are found in different proxies confirms the hypothesis that Holocene and late glacial climate variations of millennial-scale were abrupt transitions between climatic regimes as the atmosphere-ocean system reorganized in response to some forcing.” They go on to state, “although several mechanisms for such natural forcing have been advanced, recent evidence points to a potential solar forcing (Bond *et al.*, 2001) associated with ocean-atmosphere feedbacks acting as global teleconnections agents.” In addition, they note, “these transitions are identifiable across North America and presumably the world.”

Willard *et al.* (2003) examined the late Holocene (2,300 yr BP to present) record of Chesapeake Bay, along with the adjacent terrestrial ecosystem in its watershed, through the study of fossil dinoflagellate cysts and pollen derived from sediment cores. They report “several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records.”

The first of these periods of lower-than-average precipitation, which spanned the period 200 BC–AD 300, occurred during the latter part of the Roman Warm Period, as delineated by McDermott *et al.* (2001) on the basis of a high-resolution speleothem $\delta^{18}\text{O}$ record from southwest Ireland. The next such period (~AD 800–1200), in the words of the three

researchers, “corresponds to the ‘Medieval Warm Period,’ which has been documented as drier than average by tree-ring (Stahle and Cleaveland, 1994) and pollen (Willard *et al.*, 2001) records from the southeastern USA.” Other periods consisting of several decadal-scale dry intervals spanned the years AD 1320–1400 and AD 1525–1650.

The researchers also state, “mid-Atlantic dry periods generally correspond to central and southwestern USA ‘megadroughts,’ described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity.” In addition, “droughts in the late sixteenth century that lasted several decades, and those in the ‘Medieval Warm Period’ and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al.*, 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al.*, 2000; Laird *et al.*, 1996a, 1996b) and detrital clastic records (Dean, 1997).”

The work of Willard *et al.* (2003) demonstrates the reality of the millennial-scale hydrologic cycle that accompanies the millennial-scale temperature cycle responsible for producing alternating warm and cold intervals such as the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period. It also confirms the global warming of the twentieth century has not yet produced unusually strong wet and dry periods, contradicting claims that warming will exacerbate extreme climate anomalies.

Cook *et al.* (2004) developed a 1,200-year history of drought for the western half of the United States and adjacent parts of Canada and Mexico (hereafter the “West”), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index derived for 103 points on a $2.5^\circ \times 2.5^\circ$ grid, 68 of which grid points (66 percent of them) possessed reconstructions that extended back to AD 800. This reconstruction revealed “some remarkable earlier increases in aridity that dwarf the comparatively short-duration current drought in the ‘West.’” Also of great interest, “the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occurred during a ~400 year interval of overall elevated aridity from AD 900 to 1300,” which they say was “broadly consistent with the Medieval Warm Period.”

The five scientists write, “the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests anomalously warm climate conditions during that time may have contributed to

Observations: Temperature Records

the development of more frequent and persistent droughts in the “West.” After citing nine other studies that provide independent evidence of significant drought during this time period for various sub-regions of the “West,” they warn, “any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America.” If the association between warmth and drought in the “West” is robust, as their data suggest, temperatures of the latter part of the twentieth century and the first part of the twenty-first century must still be significantly less than those experienced during large segments of the Medieval Warm Period over much of western North America and the United States in particular.

Carbotte *et al.* (2004) located fossil oyster beds within the Tappan Zee area of the Hudson River estuary (New York, USA) via chirp sub-bottom and side-scan sonar surveys and retrieved sediment cores from the sites that provided shells for radiocarbon dating. The researchers found “oysters flourished during the mid-Holocene warm period,” when “summertime temperatures were 2–4°C warmer than today (e.g., Webb *et al.*, 1993; Ganopolski *et al.*, 1998).” Thereafter, they note, the oysters “disappeared with the onset of cooler climate at 4,000–5,000 cal. years BP,” but they “returned during warmer conditions of the late Holocene,” which the authors specifically identify as the Roman and Medieval Warm Periods as delineated by Keigwin (1996) and McDermott *et al.* (2001). The authors state, “these warmer periods coincide with the return of oysters in the Tappan Zee.” They also report their shell dates suggest a final “major demise at ~500–900 years BP,” which they describe as being “consistent with the onset of the Little Ice Age,” noting further that in nearby Chesapeake Bay, “Cronin *et al.* (2003) report a sustained period of cooler springtime water temperatures (by ~2–5°C) during the Little Ice Age relative to the earlier Medieval Warm Period.” Carbotte *et al.* add, “similar aged fluctuations in oyster presence are observed within shell middens elsewhere along the Atlantic seaboard,” citing results obtained from Maine to Florida.

This study of the periodic establishment and demise of oyster beds in the Hudson River estuary and elsewhere along the east coast of the United States paints a clear picture of alternating, multi-century warm and cold intervals over the past two millennia that is vastly different from the 1,000-year-long “hockey stick” temperature history of Mann *et al.* (1998, 1999) and the 2,000-year-long history

produced by Mann and Jones (2003), in which Northern Hemispheric and global mean temperatures show essentially no low-frequency variability until the advent of the twentieth century, when temperatures are portrayed as rising dramatically, allowing to the authors to incorrectly claim twentieth century warming was driven by anthropogenic CO₂ emissions.

Sridhar *et al.* (2006) studied the orientation, morphology, and internal structure of dunes in the easternmost (wettest) portion of the Nebraska Sand Hills, where shallow core and outcrop samples indicate the dunes were formed 800 to 1,000 years ago when aridity was widespread and persistent across western North America. In addition, based on wind data obtained from six meteorological stations in and near the Nebraska Sand Hills, they employed a computer program to calculate the sand-drift vectors of dunes that would form today if the sand were free to move and not held in place by prairie grass. They found the current configuration of the Sand Hill dunes could not have been created by the region’s current wind regime, in which air currents from the south in the spring and summer bring moist air from the Gulf of Mexico to the U.S. Great Plains. Instead, their work indicates the spring and summer winds that formed the dunes 800 to 1,000 years ago must have come from the southwest, bringing much drier and hotter-than-current air from the deserts of Mexico, with greatly reduced opportunities for rain.

This work clearly suggests much of western North America was likely both drier and hotter during the Medieval Warm Period, 800 to 1,000 years ago, than it is today. As Sridhar *et al.* note, “the dunes record a historically unprecedented large-scale shift of circulation that removed the source of moisture from the region during the growing season.” They suggest the resultant drier and warmer conditions may have been further “enhanced and prolonged,” as they phrase it, “by reduced soil moisture and related surface-heating effects,” which effects are not operative in our day to the degree they were 800 to 1,000 years ago, as was demonstrated by still other of Sridhar *et al.*’s computer analyses.

Rasmussen *et al.* (2006), who had previously demonstrated “speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004),” concentrated on two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1)

in the Guadalupe Mountains. Both records suggest periods of dramatic precipitation variability over the last 3,000 years, exhibiting large shifts unlike anything seen in the modern record. They also discovered the period from AD 900–1300 “includes severe drought events, consistent with tree-ring data for the western U.S. (Cook *et al.*, 2004),” but the preceding and following centuries (AD 100–750 and AD 1500–1800) “show increased precipitation variability ... coinciding with increased El Niño flooding events.”

These findings suggest moisture extremes much greater than those observed in the modern era are neither unusual nor manmade; they are simply a normal part of Earth’s natural climatic variability. In addition, Rasmussen *et al.*’s data clearly reveal the occurrence of the Medieval Warm Period, as well as the Dark Ages Cold Period that preceded it and the Little Ice Age that followed it, in terms of available moisture, for in this part of the world, global warmth is typically manifest in terms of low available moisture and global coolness is typically manifest in terms of high available moisture.

Millar *et al.* (2006) studied dead tree trunks located above the current treeline on the tephra-covered slopes of Whitewing Mountain and San Joaquin Ridge south of Mono Lake just east of the Inyo Craters in the eastern Sierra Nevada range of California (USA), identifying the species to which the tree remains belonged, dating them, and (using contemporary distributions of the species in relation to contemporary temperature and precipitation) reconstructing paleoclimate during the time they grew there. They report, “the range of dates for the deadwood samples, AD 815–1350, coincides with the period identified from multiple proxies in the Sierra Nevada and western Great Basin as the Medieval Climate Anomaly,” among which were tree-ring reconstructions indicating “increased temperature relative to present (Graumlich, 1993; Scuderi, 1993) and higher treelines (Graumlich and Lloyd, 1996; Lloyd and Graumlich, 1997), and pollen reconstructions [that] show greater abundance of fir in high-elevation communities than at present (Anderson, 1990).”

The five researchers also note “the Medieval forest on Whitewing was growing under mild, favorable conditions (warm with adequate moisture),” as indicated by “extremely low mean sensitivities [to stress] and large average ring widths.” They conclude, as reported in their paper’s abstract, annual minimum temperatures during the Medieval Climatic Anomaly

in the region they studied were “significantly warmer” (+3.2°C) “than present.” They say their results “closely compare to climate projections for California in AD 2070–2099 (Hayhoe *et al.*, 2004),” in which “average temperature increases of 2.3–5.8°C were projected.”

Malamud-Roam *et al.* (2006) conducted an extensive review of “the variety of paleoclimatic resources for the San Francisco Bay and watershed in order to identify major climate variations in the pre-industrial past, and to compare the records from the larger watershed region with the Bay records in order to determine the linkages between climate experienced over the larger watershed region and conditions in the San Francisco Bay.” This work revealed “intermittent mega-droughts of the Medieval Climate Anomaly (ca. AD 900–1350) coincided with a period of anomalously warm coastal ocean temperatures in the California Current,” and “oxygen isotope compositions of mussel shells from archaeological sites along the central coast also indicate that sea surface temperatures were slightly warmer than present.” In contrast, they note, “the Little Ice Age (ca. AD 1450–1800) brought unusually cool and wet conditions to much of the watershed,” and “notably stable conditions have prevailed over the instrumental period, i.e., after ca. AD 1850, even including the severe, short-term anomalies experienced during this period,” namely, “the severe droughts of the 1930s and the mid-1970s.” In this part of the world, therefore, peak Medieval warmth appears to have exceeded peak modern warmth. Also, as the four researchers note, when longer paleoclimate records are considered, “current drought conditions experienced in the US Southwest do not appear out of the range of natural variability.”

Benson *et al.* (2007) review and discuss possible impacts of early-eleventh, middle-twelfth, and late-thirteenth century droughts on three Native American cultures that occupied parts of the western United States (Anasazi, Fremont, Lovelock) plus another culture that occupied parts of southwestern Illinois (Cahokia). They found “population declines among the various Native American cultures were documented to have occurred either in the early-11th, middle-12th, or late-13th centuries”—AD 990–1060, 1135–1170, and 1276–1297, respectively—and “really extensive droughts impacted the regions occupied by these prehistoric Native Americans during one or more of these three time periods.” In particular, they say the middle-twelfth century drought “had the strongest impact on the Anasazi and

Observations: Temperature Records

Mississippian Cahokia cultures,” noting “by AD 1150, the Anasazi had abandoned 85% of their great houses in the Four Corners region and most of their village sites, and the Cahokians had abandoned one or more of their agricultural support centers, including the large Richland farming complex.” In addition, they write, “the sedentary Fremont appear to have abandoned many of their southern area habitation sites in the greater Unita Basin area by AD 1150 as well as the eastern Great Basin and the Southern Colorado Plateau,” so “in some sense, the 13th century drought may simply have ‘finished off’ some cultures that were already in decline.” The researchers say these “major reductions in prehistoric Native American habitation sites/population” occurred during a period of “anomalously warm” climate conditions, which characterized the Medieval Warm Period throughout much of the world at that particular time.

Graham *et al.* (2007) conducted an extensive review of Medieval Warm Period–Little Ice Age climatic conditions as revealed in a variety of proxy records obtained throughout western North America. The great balance of this evidence pointed to “generally arid conditions across much of the western and central US from as early as 400 A.D. until about 1300 A.D., followed by a rapid shift towards a wetter regime resembling modern climate.” The heart of this Medieval Climate Anomaly (MCA) “lasted from about 800–1250 A.D. and included episodes of severe centennial-scale drought,” which “affected regions stretching from northern Mexico, California and central Oregon, eastward through the Great Basin and into the western prairies of the central US.” The 11 researchers state, “medieval times witnessed a distinctive pattern of climate change in many regions around the planet,” and “as such, the findings suggest the evolution of the concept of an Atlantic-European ‘Medieval Warm Period’ into a surprisingly sharp instance of Holocene climate change with near-global manifestations.” Or as they rephrase it in the final paragraph of their paper, “the near-global scale of MCA climate change seems to be becoming more apparent.”

Stahle *et al.* (2007) used “an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook *et al.*, 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America.” During the Current Warm Period to date, “the Dust Bowl drought

of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America,” the authors found, citing the studies of Worster (1979), Diaz (1983), and Fye *et al.* (2003). During the Little Ice Age, they found three megadroughts, which they defined as “very large-scale drought[s] more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle *et al.*, 2000).” They also note, “much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine, 1994; Laird *et al.*, 2003; Cook *et al.*, 2004).” These megadroughts were so phenomenal the authors refer to them as “no-analog Medieval megadroughts.”

Climate models typically project that CO₂-induced global warming will result in more severe droughts. The much more severe and sustained megadroughts of the Little Ice Age appear to render such projections somewhat dubious. On the other hand, the still more severe and sustained no-analog megadroughts of the Medieval Warm Period would appear to bolster their projections. But the incredibly more severe droughts of that earlier period—if they were indeed related to high global air temperatures—would suggest it is not nearly as warm currently as it was during the Medieval Warm Period, when there was much less CO₂ in the air than there is today. These observations undercut the more fundamental claim that the historical rise in the air’s CO₂ content has been responsible for unprecedented twentieth century global warming that has taken Earth’s mean air temperature to a level unprecedented over the past two millennia.

Carson *et al.* (2007) developed a Holocene history of flood magnitudes in the northern Uinta Mountains of northeastern Utah from reconstructed cross-sectional areas of abandoned channels and relationships relating channel cross-sections to flood magnitudes derived from modern stream gauge and channel records. They found over the past 5,000 years the record of bankfull discharge “corresponds well with independent paleoclimate data for the Uinta Mountains,” and “during this period, the magnitude of the modal flood is smaller than modern during warm dry intervals and greater than modern during cool wet intervals.” They note “the decrease in flood magnitudes following 1000 cal yr B.P. corresponds to numerous local and regional records of warming during the Medieval Climatic Anomaly.”

The three researchers' graphical results, as shown in Figure 4.2.4.7.2.2, suggest the three largest negative departures from modern bankfull flood magnitudes (indicating greater than modern warmth) ranged from approximately 15 percent to 22 percent, as best as can be determined from visual inspection of their plotted data. These departures occurred between about 750 and 600 cal yr B.P., as determined from radiocarbon dating of basal channel-fill sediments. In addition to showing the degree of natural variability in northeastern Utah flood magnitudes throughout the Holocene has been much larger (in both positive and negative directions) than what has been observed in modern times, Carson *et al.*'s findings confirm the portion of the Medieval Warm Period between about

reconstructions designed to capture multi-centennial-scale variability (e.g., Esper *et al.*, 2002; Moberg *et al.*, 2005).” This suggests “the amplitude of natural climate variability over the past 1 k.y. is $>0.5^{\circ}\text{C}$,” they write.

Richey *et al.* then explain how “a continuous decadal-scale resolution record of climate variability over the past 1400 years in the northern Gulf of Mexico was constructed from a box core recovered in the Pigmy Basin, northern Gulf of Mexico [$27^{\circ}11.61'\text{N}$, $91^{\circ}24.54'\text{W}$],” based on climate proxies derived from “paired analyses of Mg/Ca and $\delta^{18}\text{O}$ in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages.” The four researchers report, “two multi-decadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm as, or warmer than, near-modern conditions between 1000 and 1400 yr B.P.,” and “foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was $2\text{--}2.5^{\circ}\text{C}$ below modern SST” (Figure 4.2.4.7.2.3). In addition, they found “four minima in the Mg/Ca record between 900 and 250 yr. B.P. correspond with the Maunder, Sporer, Wolf, and Oort sunspot minima.”

MacDonald *et al.* (2008) define the term “perfect drought” as “a prolonged drought that affects southern California, the Sacramento River basin and the upper Colorado River basin simultaneously,” noting the instrumental record indicates the occurrence of such droughts throughout the past century but that they “generally persist for less than five years.” That they have occurred at all, however, suggests the possibility of even longer “perfect droughts,” that could prove catastrophic for the region. The three researchers explored the likelihood of such droughts occurring in the years to come, based on dendrochronological reconstructions of the winter Palmer Drought Severity Index (PDSI)

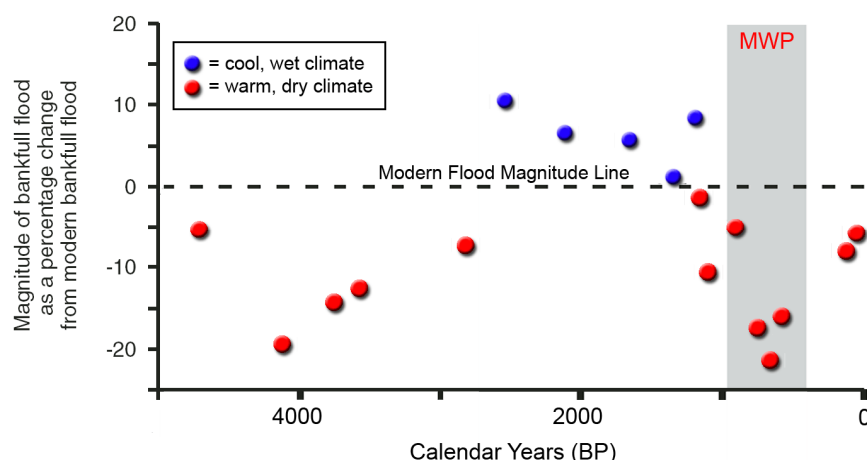


Figure 4.2.4.7.2.2. Uinta Mountains reconstructed climatic history derived from paleoflood chronology. Adapted from Carson, E.C., Knox, J.C., and Mickelson, D.M. 2007. Response of bankfull flood magnitudes to Holocene climate change, Uinta Mountains, northeastern Utah. *Geological Society of America Bulletin* 119: 1066–1078.

AD 1250 and 1400 was likely significantly warmer than current conditions.

Richey *et al.* (2007) note the variability of the hemispheric temperature reconstructions of Mann and Jones (2003) over the past one to two thousand years are “subdued ($\leq 0.5^{\circ}\text{C}$),” and their low-amplitude reconstructions are not compatible “with several individual marine records that indicate that centennial-scale sea surface temperature (SST) oscillations of $2\text{--}3^{\circ}\text{C}$ occurred during the past 1–2 k.y. (i.e., Keigwin, 1996; Watanabe *et al.*, 2001; Lund and Curry, 2006; Newton *et al.*, 2006),” just as they also differ from “tree-ring and multi-proxy

Observations: Temperature Records

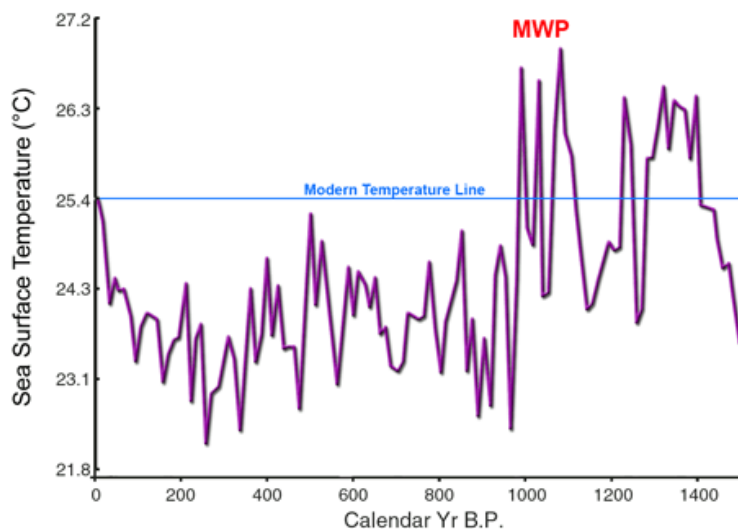


Figure 4.2.4.7.2.3. Annual Mg/Ca-derived SST anomalies for Pigmy Basin, Northern Gulf of Mexico. Adapted from Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.

in southern California over the past thousand years (Figure 4.2.4.7.2.4) and the concomitant annual discharges of the Sacramento and Colorado Rivers (Figure 4.2.4.7.2.5), under the logical assumption that what has occurred before may happen again.

MacDonald *et al.* report finding “prolonged perfect droughts (~30–60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th century during the period of the so-called ‘Medieval Climate Anomaly.’” This leads them to conclude, “prolonged perfect droughts due to natural or anthropogenic changes in radiative forcing, are a clear possibility for the near future.”

Another conclusion that can be drawn from MacDonald *et al.*’s findings is that the current warmth of the world is not yet as great as it was during the peak heat of the Medieval Warm Period, or we might have already experienced, or currently be in the process of experiencing, a multidecadal perfect drought. That such has not occurred is encouraging, but it must be remembered that even if the theory of CO₂-induced global warming is incorrect or vastly overstated, further natural warming could push the planet’s climate over the “tipping point” that initiates such a drought. That Earth has experienced no net

warming over the past decade or so is a good sign in this regard, but there is no guarantee the globe will not begin to warm again, at any time and for whatever reason. Planning for the possibility of a significant perfect drought would appear to be warranted.

McGann (2008) analyzed a sediment core retrieved from the western portion of south bay near San Francisco International Airport (37°37.83’N, 122°21.99’W) for the presence of various foraminifers as well as oxygen and carbon stable isotopes and numerous trace elements found in tests of *Elphidium excavatum*. The U.S. Geological Survey researcher states, “benthic foraminiferal abundances, stable carbon and oxygen isotopes, and Mg/Ca ratios suggest that the climate of south bay has oscillated numerous times between warm and dry, and cool and wet conditions over the past 3870 years.” “Both the Medieval Warm Period [MWP] and the Little Ice Age [LIA] are evident,” she notes. She identifies the MWP as occurring from AD 743 to 1343 and the LIA as occurring in two stages: AD 1450 to 1530 and AD 1720 to 1850. She states, the timing of the MWP “correlates well with records obtained for Chesapeake Bay (Cronin *et al.*, 2003), Long Island Sound (Thomas *et al.*, 2001; Varekamp *et al.*, 2002), California’s Sierra Nevada (Stine, 1994), coastal northernmost California (Barron *et al.*, 2004), and in the San Francisco Bay estuary in north bay at Rush Ranch (Byrne *et al.*, 2001) and south bay at Oyster Point (Ingram *et al.*, 1996).” She notes the cooler and wetter conditions of the LIA have been reported “in Chesapeake Bay (Cronin *et al.*, 2003), Long Island Sound (Thomas *et al.*, 2001; Varekamp *et al.*, 2002), coastal northernmost California (Barron *et al.*, 2004), and in the San Francisco Bay estuary at Rush Ranch (Byrne *et al.*, 2001), Petaluma Marsh (Ingram *et al.*, 1998), and in Richardson Bay (Ingram and DePaolo, 1993).” McGann also notes, “near the top of the core” foraminiferal abundances suggest, “once again, regional warming has taken place.” That warming does not appear to have returned the region to the level of sustained warmth it enjoyed during the peak warmth of the MWP.

Analyzing isotopic soil carbon measurements made on 24 modern soils and 30 buried soils scattered between latitudes 48 and 32°N and longitudes 106 and 98°W, Nordt *et al.* (2008) developed a time series of C₄ vs. C₃ plant dynamics for the past 12 ka (ka =

Climate Change Reconsidered II

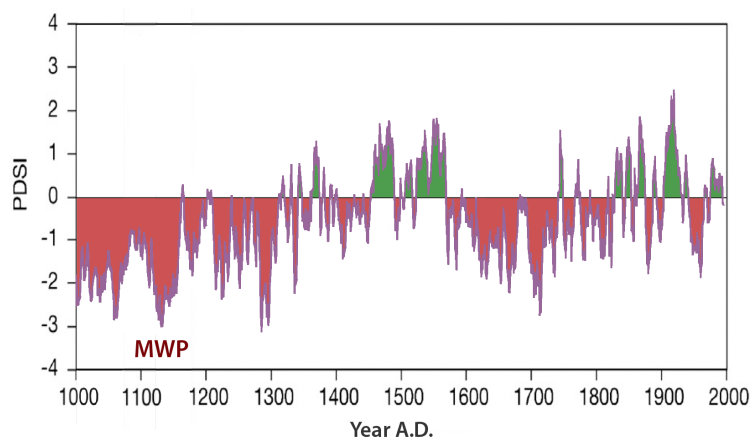


Figure 4.2.4.7.2.4. Reconstructed winter PSDI for Southern California since AD 1100. Adapted from MacDonald, G.M., Kremenetski, K.V., and Hidalgo, H.G. 2008. Southern California and the perfect drought: Simultaneous prolonged drought in Southern California and the Sacramento and Colorado River systems. *Quaternary International* 188: 11–23.

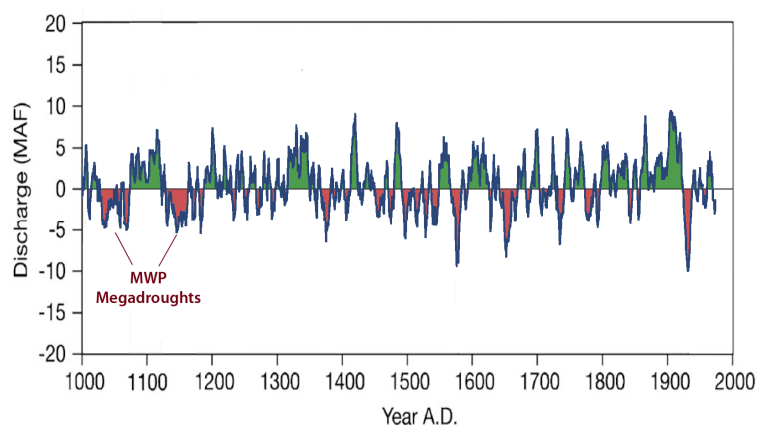


Figure 4.2.4.7.2.5. Five-year moving average of combined annual discharge deviations for the Sacramento and Colorado Rivers since AD 1100. Adapted from MacDonald *et al.* (2008).

1000 ^{14}C yr BP) in the mixed and shortgrass prairie of the U.S. Great Plains. Because the percent of soil carbon derived from C_4 plants “corresponds strongly with summer temperatures as reflected in the soil carbon pool (Nordt *et al.*, 2007; von Fischer *et al.*, 2008),” they were able to devise a history of the relative warmth of the region over this protracted period (see Figure 4.2.4.7.2.6).

Nordt *et al.*’s data suggest their region of study was slightly warmer during parts of both the Medieval and Roman Warm Periods, and it was

significantly warmer during a sizeable portion of the mid-Holocene Thermal Maximum or Climatic Optimum, as it is sometimes called. As to what caused the greater warmth of those earlier periods, Nordt *et al.* observe, “these warm intervals ... exhibit a strong correlation to increases in solar irradiance,” as per the irradiance reconstruction of Perry and Hsu (2000).

Whitlock *et al.* (2008) analyzed (at high resolution) geochemical, stable-isotope, pollen, charcoal, and diatom records found in cores obtained from Crevice Lake—located at 45.000°N, 110.578°W—to reconstruct the ecohydrologic, vegetation, and fire history of its watershed for the past 2,650 years and better understand past climate variations at the forest-steppe transition within the canyon of the Yellowstone River in northern Yellowstone National Park (YNP). The seven scientists report their many datasets were “consistent with overall warmer/drier conditions during the Medieval Climate Anomaly,” which they note had been variously dated between AD 650 and 1300 in the western United States and Great Plains. They found “the Crevice Lake data suggest a warm interval with dry winters between AD 600 and 850, followed by less dry but still warm conditions between AD 850 and 1100.” In addition, they note, “other studies in YNP indicate that trees grew above the present-day treeline and fires were more frequent in the Lamar and Soda Butte drainages between AD 750 and 1150,” citing Meyer *et al.* (1995).

Whitlock *et al.* state their data indicate “the last 150 years of environmental history since the formation of YNP have not been anomalous within the range of variability of the last 2650 years, and many of the proxy indicators suggest that 19th and 20th century variability at Crevice Lake was moderate compared with earlier extremes.” With the possible exception of the charcoal record, “all of the data show greater variability in the range of ecosystem conditions prior to the establishment of the YNP in 1872.” Thus the many parameters measured by Whitlock *et al.* indicate the YNP’s twentieth century climate is not unique and suggest much of the Medieval Warm Period was significantly warmer than the Current Warm Period has been to date, given that trees in

Observations: Temperature Records

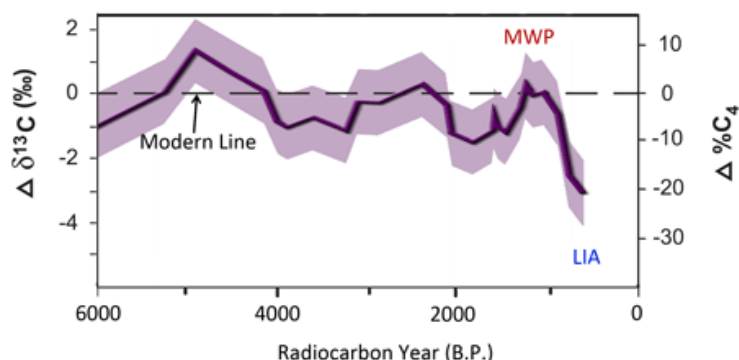


Figure 4.2.4.7.2.6. Buried soil $\Delta\delta^{13}\text{C}$ and $\Delta\%C_4$ from the Great Plains as a proxy for summer temperature. Adapted from Nordt, L., von Fischer, J., Tieszen, L., and Tubbs, J. 2008. Coherent changes in relative C_4 plant productivity and climate during the late Quaternary in the North American Great Plains. *Quaternary Science Reviews* 27: 1600–1611.

some parts of the park grew at higher elevations during the MWP than they do now.

Persico and Meyer (2009) describe their use of “beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park,” comparing “the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region.” They found “gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP are contemporaneous with increased charcoal accumulation rates in Yellowstone lakes and peaks in fire-related debris-flow activity, inferred to reflect severe drought and warmer temperatures (Meyer *et al.*, 1995).” In addition, they note, “the lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly, a time of widespread multi-decadal droughts and high climatic variability in Yellowstone National Park (Meyer *et al.*, 1995) and the western USA (Cook *et al.*, 2004; Stine, 1998; Whitlock *et al.*, 2003).” The lack of evidence for beaver activity 2,200–1,800 cal yr BP is concurrent with the Roman Warm Period. The two researchers conclude the severe droughts of these periods “likely caused low to ephemeral discharges in smaller streams, as in modern severe drought,” implying the Medieval and Roman Warm Periods were likely to have been at least as dry and warm as it is today.

Mullins *et al.* (2011) studied two sediment cores extracted from the extreme southern end of Cayuga

Lake ($\sim 42^\circ 25' \text{N}$, $76^\circ 35' \text{W}$) in central New York (USA), finding “paleolimnological evidence for the Medieval Warm Period ($\sim 1.4\text{--}0.5$ ka), which was warmer and wetter than today.” This evidence includes weight percent total carbonate (TC), total organic matter (TOM), non-carbonate inorganic terrigenous matter (TT), carbonate stable isotopes ($\delta^{18}\text{O}_{\text{TC}}$ and $\delta^{13}\text{C}_{\text{TC}}$), carbon isotope values of total organic matter ($\delta^{13}\text{C}_{\text{TOM}}$), and fossil types (gastropods, ostracods, bivalves, oögonia) and amounts. All were used to interpret past climate based on their relationship to modern climate data for the Finger Lakes region of the state. They conclude, the “data for central New York suggest a warmer, wetter climate than today.”

Routson *et al.* (2011) write, “many southwestern United States high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than those experienced during the historical period (e.g., Woodhouse and Overpeck, 1998; Cook *et al.*, 2004, 2010; Meko *et al.*, 2007).” They note, “the medieval interval (ca. AD 900 to 1400), a period with relatively warm Northern Hemisphere temperatures, has been highlighted as a period in western North America with increased drought severity, duration and extent (e.g., Stine, 1994; Cook *et al.*, 2004, 2010; Meko *et al.*, 2007; Woodhouse *et al.*, 2010),” and “the mid-12th century drought associated with dramatic decreases in Colorado River flow (Meko *et al.*, 2007), and the ‘Great Drought’ associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region (Douglass, 1929), all occurred during the medieval period.”

Routson *et al.* used a new tree-ring record derived from living and remnant bristlecone pine wood from the headwaters region of the Rio Grande River in Colorado (USA), along with other regional records, to evaluate what they describe as “periods of unusually severe drought over the past two millennia (268 BC to AD 2009).” The three researchers report the record they derived “reveals two periods of enhanced drought frequency and severity relative to the rest of the record”: “the later period, AD $\sim 1050\text{--}1330$, corresponds with medieval aridity well documented in other records,” and “the earlier period is more persistent (AD $\sim 1\text{--}400$), and includes the most pronounced event in the ... chronology: a multi-decadal-length drought during the 2nd century.” The

latter drought “includes the unsmoothed record’s driest 25-year interval (AD 148–173) as well as a longer 51-year period, AD 122–172, that has only two years with ring width slightly above the long-term mean.” In addition, “the smoothed chronology shows the periods AD 77–282 and AD 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-year record.” This second century drought, they note, “impacted a region that extends from southern New Mexico north and west into Idaho.”

The researchers note, “reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity,” and “available data also suggest that the Northern Hemisphere may have been warm during both intervals.” Despite these obviously natural occurrences, Routson *et al.* suggest the southwestern United States may experience similar or even more severe megadroughts in the future as a result of greater warming in response to anthropogenic CO₂ emissions.

Sritairat *et al.* (2012) point out “the mid-Hudson region contains freshwater peatland archives that have not been investigated,” suggesting “there is a need to identify this base-line information to assess past anthropogenic activities and climatic patterns in relation to projected shifts in climate and vegetation in the Mid-Hudson Valley region.” They explored “how climate and human impacts have influenced plant ecology, invasive species expansion, habitat loss, carbon storage, and nutrient dynamics over the past millennium based on the multiproxy analysis of sediment cores using palynology, macrofossil, sedimentological, and geochemical analyses,” working with marsh sediment cores obtained at the National Estuarine Research Reserve at Tivoli Bays on the Hudson Estuary, New York, USA.

The six scientists identified a pre-European settlement period (AD 826–1310) with a “high percentage of *Carya*, a warmth-loving species (Fowells, 1965),” a finding that “supports an increase in temperature.” At a depth dated to AD 1087 ± 72, they found a charcoal maximum, referring to it as “a feature that is also found in other Hudson river marsh cores at Piermont (Pederson *et al.*, 2005) and Iona (Peteet *et al.*, 2006).” This represents, they write, “the warm, dry Medieval Warm Period (MWP),” which they further state was “likely a result of a regional Hudson Valley MWP recorded on a larger spatial scale in other parts of North America and the globe.”

The substantial body of real-world evidence for a

generally warmer-than-present MWP, at a time when the atmosphere’s CO₂ concentration was something on the order of 285 ppm, as opposed to the 400 ppm of today, weighs heavily against the claim of higher atmospheric CO₂ concentrations invariably leading to warmer mean global temperatures. This data-grounded fact provides a concrete reason for rejecting the projections of even the very best mathematical models of how Earth’s climate is supposed to operate.

References

- Anderson, R.S. 1990. Holocene forest development and paleoclimates within the central Sierra Nevada, California. *Journal of Ecology* **78**: 470–489.
- Asmerom, Y. and Polyak, V.J. 2004. Comment on “A test of annual resolution in stalagmites using tree rings.” *Quaternary Research* **61**: 119–121.
- Barron, J.A., Heusser, L.E., and Alexander, C. 2004. High resolution climate of the past 3,500 years of coastal northernmost California. In: Starratt, S.W. and Blumquist, N.L. (Eds.) *Proceedings of the Twentieth Annual Pacific Climate Workshop*. U.S. Geological Survey, pp. 13–22.
- Benson, L.V., Berry, M.S., Jolie, E.A., Spangler, J.D., Stahle, D.W., and Hattori, E.M. 2007. Possible impacts of early-11th-, middle-12th-, and late-13th-century droughts on western Native Americans and the Mississippian Cahokians. *Quaternary Science Reviews* **26**: 336–350.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Brush, G.S. 2001. Natural and anthropogenic changes in Chesapeake Bay during the last 1000 years. *Human and Ecological Risk Assessment* **7**: 1283–1296.
- Byrne, R., Ingram, B.L., Starratt, S., Malamud-Roam, F., Collins, J.N., and Conrad, M.E. 2001. Carbon-isotope, diatom, and pollen evidence for late Holocene salinity change in a brackish marsh in the San Francisco estuary. *Quaternary Research* **55**: 66–76.
- Carbotte, S.M., Bell, R.E., Ryan, W.B.F., McHugh, C., Slagle, A., Nitsche, F., and Rubenstone, J. 2004. Environmental change and oyster colonization within the Hudson River estuary linked to Holocene climate. *Geo-Marine Letters* **24**: 212–224.
- Carson, E.C., Knox, J.C., and Mickelson, D.M. 2007. Response of bankfull flood magnitudes to Holocene climate change, Uinta Mountains, northeastern Utah. *Geological Society of America Bulletin* **119**: 1066–1078.

Observations: Temperature Records

- Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2010. Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* **25**: 48–61.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the Western United States. *Science* **306**: 1015–1018.
- Cronin, T.M., Dwyer, G.S., Kamiya, T., Schwede, S., and Willard, D.A. 2003. Medieval warm period, Little Ice Age and 20th century temperature variability from Chesapeake Bay. *Global and Planetary Change* **36**: 17–29.
- Dean, W.E. 1997. Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: evidence from varved lake sediments. *Geology* **25**: 331–334.
- Diaz, H.F. 1983. Some aspects of major dry and wet periods in the contiguous United States, 1895–1981. *Journal of Climate and Applied Meteorology* **22**: 3–16.
- Douglass, A.E. 1929. *The Secret of the Southwest Solved with Talkative Tree Rings*. Judd and Detweiler, Washington, DC, USA, pp. 736–770.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2254.
- Field, D.B. and Baumgartner, T.R. 2000. A 900 year stable isotope record of interdecadal and centennial change from the California Current. *Paleoceanography* **15**: 695–708.
- Fowells, H.A. 1965. *Silvics of Forest Trees of the United States*. U.S. Department of Agriculture, Washington, DC, USA.
- Fritz, S.C., Ito, E., Yu, Z., Laird, K.R., and Engstrom, D.R. 2000. Hydrologic variation in the northern Great Plains during the last two millennia. *Quaternary Research* **53**: 175–184.
- Fye, F.K., Stahle, D.W., and Cook, E.R. 2003. Paleoclimatic analogs to 20th century moisture regimes across the USA. *Bulletin of the American Meteorological Society* **84**: 901–909.
- Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V., and Petoukhov, V. 1998. The influence of vegetation-atmosphere-ocean interaction on climate during the mid-Holocene. *Science* **280**: 1916–1919.
- Gavin, D.G. and Brubaker, L.B. 1999. A 6000-year pollen record of subalpine meadow vegetation in the Olympic Mountains, Washington, USA. *Journal of Ecology* **87**: 106–122.
- Graham, N.E., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., and Xu, T. 2007. Tropical Pacific—mid-latitude teleconnections in medieval times. *Climatic Change* **83**: 241–285.
- Graumlich, L.J. 1990. Interaction between variables controlling subalpine tree growth: Implications for the climatic history of the Sierra Nevada. Proceedings of the Sixth Annual Pacific Climate (PACCLIM) Workshop, pp. 115–118.
- Graumlich, L.J. 1993. A 1000-yr record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* **39**: 249–255.
- Graumlich, L.J. and Lloyd, A.H. 1996. Dendroclimatic, ecological, and geomorphological evidence for long-term climatic change in the Sierra Nevada, USA. In: Dean, J.S., Meko, D.M. and Swetnam, D.W. (Eds.) *Proceedings of the International Conference on Tree Rings, Environment and Humanity*, pp. 51–59.
- Hadley, E.A., Kohn, M.H., Leonard, J.A., and Wayne, R.K. 1998. A genetic record of population isolation in pocket gophers during Holocene climatic change. *Proceedings of the National Academy of Sciences, USA* **95**: 6893–6896.
- Hayhoe, K., Cayan, D., and Field, C.B. 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Science USA* **101**: 12,422–12,427.
- Ingram, B.L., De Deckker, P., Chivas, A.R., Conrad, M.E., and Byrne, A.R. 1998. Stable isotopes, Sr/Ca, and Mg/Ca in biogenic carbonates from Petaluma Marsh, northern California, USA. *Geochemica et Cosmochimica Acta* **62**: 3229–3237.
- Ingram, B.L. and DePaolo, D.J. 1993. A 4300-year strontium isotope record of estuarine paleosalinity in San Francisco Bay, California. *Earth and Planetary Science Letters* **119**: 103–119.
- Ingram, B.L., Ingle, J.C., and Conrad, M.E. 1996. Stable isotope record of late Holocene salinity and river discharge in San Francisco Bay, California. *Earth and Planetary Science Letters* **141**: 237–247.
- Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.
- Laird, K.R., Cumming, B.F., Wunsam, S., Rusak, J.A., Oglesby, R.J., Fritz, S.C., and Leavitt, P.R. 2003. Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proceedings of the National Academy of Sciences USA* **100**: 2483–2488.
- Laird, K.R., Fritz, S.C., Grimm, E.C., and Mueller, P.G. 1996a. Century-scale paleoclimatic reconstruction from

Climate Change Reconsidered II

Moon Lake, a closed-basin lake in the northern Great Plains. *Limnology and Oceanography* **41**: 890–902.

Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F. 1996b. Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature* **384**: 552–554.

Lloyd, A.H. and Graumlich, L.J. 1997. Holocene dynamics of the tree line forests in the Sierra Nevada. *Ecology* **78**: 1199–1210.

Lund, D.C. and Curry, W. 2006. Florida current surface temperature and salinity variability during the last millennium. *Paleoceanography* **21**: 10.1029/2005PA001218.

MacDonald, G.M., Kremenetski, K.V., and Hidalgo, H.G. 2008. Southern California and the perfect drought: Simultaneous prolonged drought in Southern California and the Sacramento and Colorado River systems. *Quaternary International* **188**: 11–23.

Malamud-Roam, F.P., Ingram, B.L., Hughes, M., and Florsheim, J.L. 2006. Holocene paleoclimate records from a large California estuarine system and its watershed region: linking watershed climate and bay conditions. *Quaternary Science Reviews* **25**: 1570–1598.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.

McGann, M. 2008. High-resolution foraminiferal, isotopic, and trace element records from Holocene estuarine deposits of San Francisco Bay, California. *Journal of Coastal Research* **24**: 1092–1109.

Meko, D.M., Woodhouse, C.A., Baisan, C.H., Knight, T., Lukas, J.J., Hughes, M.K., and Salzer, W. 2007. Medieval drought in the Upper Colorado River Basin. *Geophysical Research Letters* **34**: 10.1029/2007GL029988.

Meyer, G.A., Wells, S.G., and Jull, A.J.T. 1995. Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**: 1211–1230.

Millar, C.I., King, J.C., Westfall, R.D., Alden, H.A., and Delany, D.L. 2006. Late Holocene forest dynamics, volcanism, and climate change at Whitewing Mountain and San Joaquin Ridge, Mono County, Sierra Nevada, CA, USA. *Quaternary Research* **66**: 273–287.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Mullins, H.T., Patterson, W.P., Teece, M.A., and Burnett, A.W. 2011. Holocene climate and environmental change in central New York (USA). *Journal of Paleolimnology* **45**: 243–256.

Newton, A., Thunell, R., and Stott, L. 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters* **33**: 10.1029/2006GL027234.

Nordt, L., von Fischer, J., and Tieszen, L. 2007. Late Quaternary temperature record from buried soils of the North American Great Plains. *Geology* **35**: 159–162.

Nordt, L., von Fischer, J., Tieszen, L., and Tubbs, J. 2008. Coherent changes in relative C4 plant productivity and climate during the late Quaternary in the North American Great Plains. *Quaternary Science Reviews* **27**: 1600–1611.

Patterson, W.P. 1998. North American continental seasonality during the last millennium: high-resolution analysis of sagittal otoliths. *Palaeogeography, Palaeoclimatology, Palaeoecology* **138**: 271–303.

Pederson, D.C., Peteet, D.M., Kurdyla, D., and Guilderson, T. 2005. Medieval warming, little ice age, and European impact on the environment during the last millennium in the lower Hudson valley, New York, USA. *Quaternary Research* **63**: 238–249.

Perry, C.A. and Hsu, K.J. 2000. Geophysical, archaeological, and historical evidence support a solar-output model for climate change. *Proceedings of the National Academy of Sciences* **97**: 12,433–12,438.

Persico, L. and Meyer, G. 2009. Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming. *Quaternary Research* **71**: 340–353.

Peteet, D.M., Peteet, D., Pederson, D., Kurdyla, D., and Guilderson, T. 2006. Hudson River paleoecology from marshes. In: *Hudson River Fishes and Their Environment*. American Fisheries Society Monograph.

Rasmussen, J.B.T., Polyak, V.J., and Asmerom, Y. 2006. Evidence for Pacific-modulated precipitation variability during the late Holocene from the southwestern USA. *Geophysical Research Letters* **33**: 10.1029/2006GL025714.

Observations: Temperature Records

- Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.
- Schreiner, E.G. 1994. Subalpine and alpine plant communities. In: Houston, D.B., Schreiner, E.G., and Moorhead, B.B. (Eds.) *Mountain Goats in Olympic National Park: Biology and Management of an Introduced Species*. Olympic National Park, National Park Service, Port Angeles, Washington, pp. 242–250.
- Scuderi, L. 1993. A 2,000-year record of annual temperatures in the Sierra Nevada Mountains. *Science* **259**: 1433–1436.
- Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J., and Rowe, C.M. 2006. Large wind shift on the Great Plains during the Medieval Warm Period. *Science* **313**: 345–347.
- Stahle, D.W. and Cleaveland, M.K. 1994. Tree-ring reconstructed rainfall over the southeastern U.S.A. during the Medieval Warm Period and Little Ice Age. *Climatic Change* **26**: 199–212.
- Stahle, D.W., Cleaveland, M.K., and Hehr, J.G. 1985. A 450-year drought reconstruction for Arkansas, United States. *Nature* **316**: 530–532.
- Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell, M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and Luckman, B.H. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, Transactions, American Geophysical Union* **81**: 212, 225.
- Stahle, D.W., Fye, F.K., Cook, E.R., and Griffin, R.D. 2007. Tree-ring reconstructed megadroughts over North America since A.D. 1300. *Climatic Change* **83**: 133–149.
- Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.
- Stine, S. 1998. Medieval climatic anomaly in the Americas. In: Issar, A.S. and Brown, N. (Eds.) *Water, Environment and Society in Times of Climatic Change*. Kluwer Academic Publishers, pp. 43–67.
- Thomas, E., Shackelford, J., Varekamp, J.C., Buchholtz Ten Brink, M.R., and Mccray, E.L. 2001. Foraminiferal records of environmental change in Long Island Sound. *Geological Society of America, Abstracts with Program* **33**(1): A-83.
- Varekamp, J.C., Thomas, E., Lugolobi, F., and Buchholtz ten Brink, M.R. 2002. The paleo-environmental history of Long Island Sound as traced by organic carbon, biogenic silica and stable isotope/trace element studies in sediment cores. *Proceedings of the 6th Biennial Long Island Sound Research Conference*, Groton, CT.
- Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E., and Sawada, M.C. 2002. Widespread evidence of 1500 yr climate variability in North America during the past 14,000 yr. *Geology* **30**: 455–458.
- von Fischer, J.C., Tieszen, L.L., and Schimel, D.S. 2008. Climate controls on C3 vs. C4 productivity in North American grasslands from carbon isotope composition of soil organic matter. *Global Change Biology* **14**: 1–15.
- Watanabe, T., Winter, A., and Oba, T. 2001. Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and $^{18}\text{O}/^{16}\text{O}$ ratios in corals. *Marine Geology* **173**: 21–35.
- Webb III, T., Bartlein, P.J., Harrison, S.P., and Anderson, K.H. 1993. Vegetation, lake levels, and climate in eastern North America for the past 18000 years. In: Wright, H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrott, F.A., and Bartlein, P.J. (Eds.) *Global Climates Since the Last Glacial Maximum*, University of Minnesota Press, Minneapolis, Minnesota, USA, pp. 415–467.
- Whitlock, C., Dean, W., Rosenbaum, J., Stevens, L., Fritz, S., Bracht, B., and Power, M. 2008. A 2650-year-long record of environmental change from northern Yellowstone National Park based on a comparison of multiple proxy data. *Quaternary International* **188**: 126–138.
- Whitlock, C., Shafer, S.L., and Marlon, J. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management* **178**: 5–21.
- Willard, D.A., Cronin, T.M., and Verardo, S. 2003. Late-Holocene climate and ecosystem history from Chesapeake Bay sediment cores, USA. *The Holocene* **13**: 201–214.
- Willard, D.A., Weimer, L.M., and Holmes, C.W. 2001. The Florida Everglades ecosystem, climatic and anthropogenic impacts over the last two millennia. In: Wardlaw, B.R. (Ed.) *Paleoecology of South Florida*. *Bulletins of American Paleontology* **361**: 41–55.
- Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W., and Cook, E.R. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences USA* **107**: 21,283–21,288.
- Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the Central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.
- Worster, D. 1979. *Dust Bowl: The Southern Plains in the 1930s*. Oxford University Press.

4.2.4.7.3 Central America

Lachniet *et al.* (2004) generated a high-resolution oxygen-isotope rainfall record of the Central American Monsoon for the Isthmus of Panama from a U/Th-dated stalagmite that spanned the period 180 BC to AD 1310. The work revealed pronounced hydrologic anomalies during medieval times, with the driest conditions occurring between AD 900 and 1310, but especially during the AD 1100–200 “High Medieval” when western European temperatures were reported to be “anomalously high,” as Lachniet *et al.* put it. The seven scientists state, “the correspondence between warm medieval temperatures and dry hydrologic anomalies in Panama supports a large-scale Medieval Climatic Anomaly that may have been global in extent, and involved atmospheric circulation reorganizations that are linked to ENSO.”

Hodell *et al.* (1995) examined a sediment core retrieved in 1993 from Lake Chichanacanab in the center of the northern Yucatan Peninsula of Mexico (19°50′–19°57′N, 88°45′–88°46′W), finding evidence of a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800–1000). Subsequently, based on two additional sediment cores retrieved from the same location in 2000, Hodell *et al.* (2001) determined the massive drought likely occurred in two distinct phases (750–875 and 1000–1075). Hodell *et al.* (2005) returned to Lake Chichanacanab in March 2004 to retrieve additional sediment cores in some of the deeper parts in the lake, with multiple cores being taken from its deepest point.

Depth profiles of bulk density data were obtained by means of gamma-ray attenuation, as were profiles of reflected red, green, and blue light via a digital color line-scan camera. The researchers report, “the data revealed in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization.” They also showed “the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions,” which “included an early phase (ca 770–870) and late phase (ca 920–1100).” They report, “the bipartite drought history inferred from Chichanacanab is supported by oxygen isotope records from nearby Punta Laguna,” and “the general pattern is also consistent with findings from the Cariaco Basin off northern Venezuela (Haug *et al.*, 2003), suggesting that the Terminal Classic Drought was a

widespread phenomenon and not limited to north-central Yucatan.” It appears the Terminal Classic Drought that led to the demise of Mayan civilization likely occurred during the climatic transition between the Dark Ages Cold Period and the Medieval Warm Period, when increasing temperatures may have exacerbated land water loss via evaporation in the midst of a prolonged period of significantly reduced precipitation.

Almeida-Lenero *et al.* (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala (19°03′N, 99°18′W) and nearby Lake Quila (19°04′N, 99°19′W) in the central Mexican highlands about 65 km southwest of Mexico City. They determined it was generally more humid in the central Mexican highlands during the mid-Holocene than at present. Thereafter, there was a gradual drying of the climate; their data from Lake Zempoala indicate “the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene,” and this interval of 200 years “coincides with the collapse of the Maya civilization.” They report their data from Lake Quila were also “indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP.” They state, “climatic aridity during this time was also noted by Metcalfe *et al.* (1991) for the Lerma Basin [central Mexico],” “dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982),” and “dry conditions were also reported for [Mexico’s] Zacapu Basin (Metcalfe, 1995) and for [Mexico’s] Yucatan Peninsula (Curtis *et al.*, 1996, 1998; Hodell *et al.*, 1995, 2001).”

Barron and Bukry (2007) analyzed high-resolution records of diatoms and silicoflagellate assemblages spanning the past 2,000 years derived from sediment cores extracted from three sites on the eastern slope of the Gulf of California, comprising core BAM80 E-17 retrieved at 27.92°N, 111.61°W; core NH01-21 retrieved at 26°17.39′N, 109°55.24′W; and core NH01-26 retrieved at 24°16.78′N, 108°11.65′W. In all three cores, the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures) was found to be far greater during the Medieval Warm Period than at any other time over the 2,000-year period studied, and during the Current Warm Period its relative abundance was lower than the 2,000-year mean, also in all three of the sediment cores (Figure 4.2.4.7.3.1). In addition, the first of the cores exhibited elevated *A. nodulifera*

Observations: Temperature Records

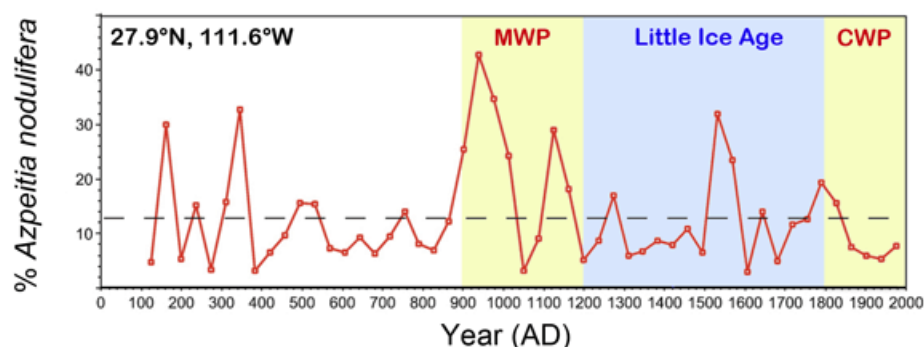


Figure 4.2.4.7.3.1. Relative abundance of *Azpeitia nodulifera*, a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures, derived from sediment cores extracted from three sites on the eastern slope of the Gulf of California. Adapted from Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* 62: 115–139.

abundances from the start of the record to about AD 350, during the latter part of the Roman Warm Period, as well as between AD 1520 and 1560. By analyzing radiocarbon production data, the two researchers found the changes in climate they identified likely were driven by solar forcing.

Metcalf and Davies (2007) synthesized the findings of a variety of paleoclimate studies based on analyses of the sediment records of several crater lakes and lakes formed by lava dams across the Trans Mexican Volcanic Belt of central Mexico with an absolute chronology provided by radiocarbon dates extending back to 1,500 ^{14}C yr BP. Noting the degree of coherence among the records is “remarkable,” Metcalf and Davis report, “dry conditions, probably the driest of the Holocene, are recorded over the period 1,400 to 800 ^{14}C yr BP (ca. AD 700–1200).” They also observe “the present day climate of central Mexico is typical of most of the country.” The researchers state their work is “consistent with results from the Yucatan Peninsula (Hodell *et al.*, 1995, 2005) ... and from the Cariaco basin (Haug *et al.*, 2003) and the Isthmus of Panama (Lachniet *et al.*, 2004).” In addition, Mayewski *et al.* (2004) have identified the central portion of this period (AD 800 to 1000) as a time of truly global anomalous climate.

Thus, Metcalf and Davies provide convincing evidence that one of the strongest manifestations of the Medieval Warm Period throughout most of Mexico was a major lack of moisture, which in this particular part of the world delineates the Medieval Warm Period better than the epoch’s primary defining

characteristic of elevated temperature.

Hodell *et al.* (2007) inferred “the Holocene paleoclimate history of the northeastern Yucatan Peninsula by comparing physical and chemical properties in two sediment cores from Lake Punta Laguna,” located approximately 20 km NNE of Coba, discussing “the potential implications for Maya cultural transformation.” They report the Terminal Classic Collapse of 750–1050 A.D., which they describe as “the greatest cultural discontinuity prior to Spanish contact,” can “be

viewed as a series of transformations, occurring first in the south during the late eighth and ninth centuries A.D., followed by a similar decline in the north in the tenth century A.D.” They also found evidence for “lower lake level and drier climate at about the same time as each major discontinuity in Maya cultural history.”

According to the three researchers, “the fact that both major climatic changes and cultural transformations occurred in the Terminal Classic Period between 750 and 1050 A.D. is probably not coincidental.” Global weather patterns indeed may have changed in such a way over this period that the recurring multi-year dry spells characteristic of the Terminal Classic Period became increasingly severe and difficult for the Maya to bear, likely leading to the civilization’s collapse at the very peak of the global Medieval Warm Period.

Polk *et al.* (2007) analyzed environmental changes on Belize’s Vaca Plateau via “vegetation reconstruction using $\delta^{13}\text{C}$ values of fulvic acids extracted from cave sediments,” which provide “a proxy record of Maya alteration of the environment through agricultural practices,” in conjunction with “speleothem carbon and oxygen isotope data from another nearby cave in the study area” that “provide information regarding climate variability.”

Starting at approximately AD 500, according to the three U.S. researchers, increasingly negative $\delta^{13}\text{C}$ values in the sediment record indicate “the declining practice of agriculture,” which they say is “characteristic of a C_3 -dominated environment

receiving little contribution from the isotopically heavier C₄ agricultural plants.” This inference makes sense because the period of initial agricultural decline coincides with the well-known Maya Hiatus of AD 530 to 650, which was driven by an increasing “lack of available water resources needed to sustain agriculture,” and the study area “would likely have been among the first sites to be affected by aridity due to its naturally well-drained upland terrain, causing a shift away from agricultural land use that preceded [that of] many other lowland areas.”

Polk *et al.* report their $\delta^{13}\text{C}$ values indicate that as early as AD 800 the Vaca Plateau “was no longer used for agriculture, coinciding with the Terminal Classic Collapse” of the Maya, which Hodell *et al.* (2007) identified as taking place between AD 750 and 1050, indicating the Ix Chel archaeological site on the Vaca Plateau was one of the first to bear witness to the demise of the Maya people.

These discoveries of Polk *et al.* are just another example of the devastating human consequences of the catastrophic droughts that plagued many parts of North, Central, and northern tropical South America during the global Medieval Warm Period. They also constitute yet another important testament to the reality of the MWP and its global reach.

Dominguez-Vazquez and Islebe (2008) derived a 2,000-year history of regional drought using radio-carbon dating and pollen analyses of a sediment core retrieved from the shore of Naja Lake (16°59'27.6"N, 91°35'29.6"W), located near the Lacandon Forest Region in the state of Chiapas in southeastern Mexico, inhabited by the Maya since the early Formative Period (ca. 1,000 BC). The researchers write, “a marked increase in *Pinus* pollen, together with a reduction in lower montane rain forest taxa, is interpreted as evidence for a strong, protracted drought from 1260 to 730 years BP,” which they characterize as “the most severe” of the record. They note, “the drought coincides with the Maya classic collapse and represents the most pronounced dry period of the last 2,000 years in the Lacandon area.”

Thus, much as the higher temperatures of the Medieval Warm Period in Greenland benefited the Vikings, its greater dryness in southeastern Mexico cursed the Maya, who had called that region home for close to 2,000 years. This contrast exemplifies how millennial-scale climate change can have vastly different effects on human societies in different parts of the world. It is also equally clear these changes of the past occurred independently of any changes in the air's CO₂ content, and if the world is in the initial

stages of a new warming phase of this cycle, both positive and negative impacts can be expected.

Escobar *et al.* (2010) used sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula to “(1) investigate ‘within-horizon’ stable isotope variability ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) measured on multiple, single ostracod valves and gastropod shells, (2) determine the optimum number of individuals required to infer low-frequency climate changes, and (3) evaluate the potential for using intra-sample $\delta^{18}\text{O}$ variability in ostracod and gastropod shells as a proxy measure for high-frequency climate variability.” The five researchers state the resulting data “allow calculation of mean isotope values and thus provide a rough estimate of the low-frequency variability over the entire sediment sequence.” These results indicate “relatively dry periods were persistently dry whereas relatively wet periods were composed of wet and dry times.”

These findings “confirm the interpretations of Hodell *et al.* (1995, 2007) and Curtis *et al.* (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period.” The scientists determined the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the past 3,000 years, but also a persistently dry period. They note, “the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability.”

Brunelle *et al.* (2010) collected sediments from a cienega (a wet, marshy area where groundwater bubbles to the surface) located at approximately 31.3°N, 109.3°W in the drainage of Black Draw Wash/Rio de San Bernardino of southeastern Arizona (USA) and northeastern Sonora (Mexico) during the summers of 2004 and 2005, sampling the incised channel wall of the Rio de San Bernardino arroyo and the cienega surface of the San Bernardino National Wildlife Refuge “for charcoal analysis to reconstruct fire history,” as well as pollen data to infer something about climate. The team of U.S. and Mexican researchers report “preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity,” and the results from the fire reconstruction “show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly.” During the latter period, from approximately AD 900 to 1260, “background charcoal reaches the highest level of the entire record

and fire peaks are frequent,” after which, they report “the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al.*, 2004).”

Figueroa-Rangel *et al.* (2010) constructed a 1,300-year history of the cloud forest vegetation dynamics of the Sierra de Manantlan Biosphere Reserve (SMBR) in west-central Mexico via analyses of fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35’32”N, 104°16’56”W). This reconstruction revealed “during intervals of aridity, cloud forest taxa tend to become reduced,” whereas “during intervals of increased humidity, the cloud forest thrives.” The three researchers inferred from their reconstruction a major dry period that lasted from approximately AD 750 to 1150 in the SMBR.

They write, “results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region; in central Mexico (Metcalf and Hales, 1994; Metcalfe, 1995; Arnauld *et al.*, 1997; O’Hara and Metcalfe, 1997; Almeida-Lenero *et al.*, 2005; Ludlow-Wiechers *et al.*, 2005; Metcalfe *et al.*, 2007); lowlands of the Yucatan Peninsula (Hodell *et al.*, 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug *et al.*, 2003).” They also note “the causes associated to this phase of climate change have been attributed to solar activity (Hodell *et al.*, 2001; Haug *et al.*, 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe *et al.*, 2000; Hodell *et al.*, 2005a,b; Berrio *et al.*, 2006) and to ENSO variability (Metcalfe, 2006).” The timeframe of this significant dry period coincides well with the broad central portion of the Medieval Warm Period, and this correspondence further harmonizes with the dry period’s temporal association with enhanced solar activity and a southward shift of the ITCZ.

Focusing on the North American countries south of the United States southern border, the studies reviewed here clearly demonstrate the existence of a Medieval Warm Period far removed from the North Atlantic Ocean, contrary to the IPCC’s dismissal of the MWP as a minor, regional phenomenon. To the contrary, the MWP was global in extent, as demonstrated by data obtained on all of Earth’s continents, and it was characterized by temperatures generally higher than those of the recent past and the present, in an atmosphere with a CO₂ concentration of only 285 ppm, compared to the 400 ppm of today.

References

- Almeida-Lenero, L., Hooghiemstra, H., Cleef, A.M., and Van Geel, B. 2005. Holocene climatic and environmental change from pollen records of Lakes Zempoala and Quila, central Mexican highlands. *Review of Palaeobotany and Palynology* **136**: 63–92.
- Arnauld, C., Metcalfe, S., and Petrequin, P. 1997. Holocene climatic change in the Zacapu Lake Basin, Michoacan: synthesis of results. *Quaternary International* **43/44**: 173–179.
- Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* **62**: 115–139.
- Berrio, J.C., Hooghiemstra, H., van Geel, B., and Ludlow-Wiechers, B. 2006. Environmental history of the dry forest biome of Guerrero, Mexico, and human impact during the last c. 2700 years. *The Holocene* **16**: 63–80.
- Brunelle, A., Minckley, T.A., Blissett, S., Cobabe, S.K., and Guzman, B.L. 2010. A ~8000 year fire history from an Arizona/Sonora borderland cienega. *Journal of Arid Environments* **24**: 475–481.
- Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Curtis, J., Brenner, M., Hodell, D., Balser, R., Islebe, G.A., and Hooghiemstra, H. 1998. A multi-proxy study of Holocene environmental change in the Maya Lowlands of Peten Guatemala. *Journal of Paleolimnology* **19**: 139–159.
- Curtis, J., Hodell, D., and Brenner, M. 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. *Quaternary Research* **46**: 37–47.
- Dominguez-Vazquez, G. and Islebe, G.A. 2008. Protracted drought during the late Holocene in the Lacandon rain forest, Mexico. *Vegetation History and Archaeobotany* **17**: 327–333.
- Escobar, J., Curtis, J.H., Brenner, M., Hodell, D.A., and Holmes, J.A. 2010. Isotope measurements of single ostracod valves and gastropod shells for climate reconstruction: evaluation of within-sample variability and determination of optimum sample size. *Journal of Paleolimnology* **43**: 921–938.
- Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., and Aeschlimann, B. 2003. Climate and the collapse of Maya civilization. *Science* **299**: 1731–1735.
- Hodell, D.A., Brenner, M., and Curtis, J.H. 2005a. Terminal Classic drought in the northern Maya lowlands

inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews* **24**: 1413–1427.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2007. Climate and cultural history of the Northeastern Yucatan Peninsula, Quintana Roo, Mexico. *Climatic Change* **83**: 215–240.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1369.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E. I.-C., Albornaz-Pat, A., and Guilderson, T.P. 2005b. Climate change on the Yucatan Peninsula during the Little Ice Age. *Quaternary Research* **63**: 109–121.

Hodell, D.A., Curtis, J.H., and Brenner, M. 1995. Possible role of climate in the collapse of Classic Maya civilization. *Nature* **375**: 391–394.

Lachniet, M.S., Burns, S.J., Piperno, D.R., Asmerom, Y., Polyak, V.J., Moy, C.M., and Christenson, K. 2004. A 1500-year El Niño/Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite. *Journal of Geophysical Research* **109**: 10.1029/2004JD004694.

Ludlow-Wiechers, B., Almeida-Lenero, L., and Islebe, G. 2005. Paleoeological and climatic changes of the Upper Lerma Basin, Central Mexico during the Holocene. *Quaternary Research* **64**: 318–332.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveland, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

Metcalfe, S.E. 1995. Holocene environmental change in the Zacapu Basin, Mexico: a diatom based record. *The Holocene* **5**: 196–208.

Metcalfe, S.E. 2006. Late Quaternary environments of the northern deserts and central transvolcanic belt of Mexico. *Annals of the Missouri Botanical Garden* **93**: 258–273.

Metcalfe, S. and Davies, S. 2007. Deciphering recent climate change in central Mexican lake records. *Climatic Change* **83**: 169–186.

Metcalfe, S.E., Davies, S.J., Braisby, J.D., Leng, M.J., Newton, A.J., Terrett, N.L., and O'Hara, S.L. 2007. Long-term changes in the Patzcuaro Basin, central Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* **247**: 272–295.

Metcalfe, S.E. and Hales, P.E. 1994. Holocene diatoms from a Mexican crater lake—La Piscina Yuriria. In: *Proceedings of the 11th International Diatom Symposium*,

San Francisco, USA, 1990 **17**: 155–171. California Academy of Sciences, San Francisco, California, USA.

Metcalfe, S.E., O'Hara, S.L., Caballero, M., and Davies, S.J. 2000. Records of Late Pleistocene-Holocene climatic change in Mexico—a review. *Quaternary Science Reviews* **19**: 699–721.

Metcalfe, S.E., Street-Perrott, F.A., Perrott, R.A., and Harkness, D.D. 1991. Palaeolimnology of the Upper Lerma Basin, central Mexico: a record of climatic change and anthropogenic disturbance since 11,600 yr B.P. *Journal of Paleolimnology* **5**: 197–218.

O'Hara, S.L. and Metcalfe, S.E. 1997. The climate of Mexico since the Aztec period. *Quaternary International* **43/44**: 25–31.

Polk, J.S., van Beynen, P.E., and Reeder, P.P. 2007. Late Holocene environmental reconstruction using cave sediments from Belize. *Quaternary Research* **68**: 53–63.

Watts, W.A. and Bradbury, J.P. 1982. Paleoeological studies at Lake Patzcuaro on the West Central Mexican plateau and at Chalco in the Basin of Mexico. *Quaternary Research* **17**: 56–70.

Webster, J.W., Brook, G.A., Railsback, L.B., Cheng, H., Edwards, R.L., Alexander, C., and Reeder, P.P. 2007. Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya collapse. *Palaeogeography, Palaeoclimatology, Palaeoecology* **250**: 1–17.

4.2.4.8 Oceans

As indicated in the introduction of Section 4.2.4, data presented in numerous peer-reviewed scientific studies reveal the existence of a global Medieval Warm Period (MWP) that occurred approximately 1,000 years ago when atmospheric CO₂ concentrations were approximately 30 percent lower than they are today. This natural fluctuation in climate is likely the product of a millennial-scale oscillation responsible for ushering in the relative warmth of the present day. This subsection highlights work that has documented the MWP, and various characteristics of it, in the world's oceans.

4.2.4.8.1 The Past Several Millennia

Gagan *et al.* (1998) used a double-tracer technique based on Sr/Ca and ¹⁸O/¹⁶O ratios in the skeletal remains of corals from Australia's Great Barrier Reef to infer climatic conditions for that region about 5,350 years ago. Impressed with their use of such coupled data, which allowed them to more accurately

Observations: Temperature Records

determine sea surface temperatures (SSTs) than had been possible in the past, Beck (1998) stated in his commentary on their paper that the new approach “promises to elucidate many important new clues about the dynamics of the coupled ocean-atmosphere-climate system for climate modelers to digest.”

Gagan *et al.*'s work indicated the tropical ocean surface some 5,350 years ago, when there was much less CO₂ in the air than there is today, was 1.2°C warmer than the mean that prevailed throughout the early 1990s. This finding accorded well with terrestrial pollen and tree-line elevation records from elsewhere in the tropical Pacific for the entire period from 7,000 to 4,000 years ago. In addition, their work suggests the higher tropical SSTs of that time likely enhanced evaporation from the tropical Pacific, and the extra latent heat and moisture thereby exported to higher latitudes may have helped to maintain the equable climates known to have characterized the extra-tropics during this time.

McManus *et al.* (1999) examined a deep-sea sediment core from the eastern North Atlantic Ocean that included the last five glacial-interglacial cycles. They noted significant temperature oscillations throughout the record, which were of much greater amplitude during glacial as opposed to interglacial periods. SSTs, for example, oscillated between 1° and 2°C during warm interglacials, but varied between 4° and 6°C during colder glacial times. They conclude climatic variability on millennial time scales “has thus been the rule, rather than the exception.” It is likely the warming of the last century or so was simply the most recent manifestation of a naturally recurring phenomenon unrelated to the concurrent increase in the atmosphere's CO₂ concentration. In addition, McManus *et al.*'s findings clearly contradict the contention that any future global warming will result in greater, and therefore more harsh, temperature extremes; their half-million-year record clearly indicates temperature variability during warmer times is more muted than it is during colder times.

Adding 50,000 years to the interval investigated by McManus *et al.*, Herbert *et al.* (2001) analyzed proxy SSTs over the past 550,000 years via data obtained from several marine sediment cores taken along the western coast of North America, from 22°N at the southern tip of the Baja Peninsula to 42°N off the coast of Oregon. They found “the previous interglacial produced surface waters several degrees warmer than today,” such that “waters as warm as those now at Santa Barbara occurred along the Oregon margin.” Their data indicate the peak SSTs of

the current interglacial were 1° to 4°C cooler than the peak SSTs of all four of the preceding interglacial periods.

Raymo *et al.* (1998) studied physical and chemical characteristics of an ocean sediment core retrieved from a site south of Iceland. They found millennial-scale oscillations of climate were occurring more than one million years ago in a region of the North Atlantic that has been shown to strongly influence circum-Atlantic, and possibly global, climate. These oscillations appeared to be similar in character and timing to the Dansgaard-Oeschger cycles of the most recent glacial epoch.

Because the climate of the early Pleistocene was too warm to support the growth and development of the large, 100,000-year ice sheets characteristic of the late Pleistocene, and because similar millennial-scale climate oscillations are evident in both time periods, Raymo *et al.* conclude millennial-scale climate oscillations “may be a pervasive and long-term characteristic of Earth's climate, rather than just a feature of the strong glacial-interglacial cycles of the past 800,000 years.” Since the millennial-scale climate oscillations of both periods have not been attributed to variations in atmospheric CO₂ concentration, there would appear to be little reason to attribute the warming of the past century or so to the concurrent increase in the atmosphere's CO₂ concentration, or to expect any further rise in CO₂ content to trigger significant warming.

References

- Beck, W. 1998. Warmer and wetter 6000 years ago? *Science* **279**: 1003–1004.
- Gagan, M.K., Ayliffe, L.K., Hopley, D., Cali, J.A., Mortimer, G.E., Chappell, J., McCulloch, M.T., and Head, M.J. 1998. Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific. *Science* **279**: 1014–1017.
- Herbert, T.D., Schuffert, J.D., Andreasen, D., Heusser, L., Lyle, M., Mix, A., Ravelo, A.C., Stott, L.D., and Herguera, J.C. 2001. Collapse of the California Current during glacial maxima linked to climate change on land. *Science* **293**: 71–76.
- McManus, J.F., Oppo, D.W., and Cullen, J.L. 1999. A 0.5-million-year record of millennial-scale climate variability in the North Atlantic. *Science* **283**: 971–974.
- Raymo, M.E., Ganley, K., Carter, S., Oppo, D.W., and McManus, J. 1998. Millennial-scale climate instability during the early Pleistocene epoch. *Nature* **392**: 699–702.

4.2.4.8.2 The Past Few Centuries

In order to understand the present—and potentially predict the future—it is helpful to have a correct understanding of the past, and nowhere is this more important than in the ongoing debate over the impact of anthropogenic CO₂ emissions on global climate. In this summary, we review what has been learned about this subject based on proxy sea surface temperature data pertaining to the past few centuries.

Fjellsa and Nordberg (1996) derived a history of the Holocene distribution of the dinoflagellate *Gymnodinium catenatum* from an ocean sediment core extracted from the Kattegat region of the North Sea between Sweden and Denmark (56°32'48" N, 12°11'15" E). This work revealed an early abundance of the species at about 4,300–4,500 yr BP. Then, in connection with what they called a “climatic deterioration, the species decreased abruptly and subsequently disappeared.” It reestablished its presence some time later and, as they describe it, “occurred in massive ‘blooms’ during the so-called mediaeval warm epoch round about 700–800 yr BP.” They add, “at the time of the so-called Little Ice Age, approximately 300 yr BP, *G. catenatum* again became extinct in the Kattegat area.”

Fjellsa and Nordberg report “there appears to be a close relationship between climatic fluctuations and the presence and abundances of *G. catenatum*, which from its present ecology is considered a warmer water species.” They conclude the two bloom periods were “characterized as warmer periods with climatic optima correlated to the peak phases,” noting “the most massive blooms took place during the so-called ‘Medieval warm epoch.’”

The two researchers also report, “cysts from *G. catenatum* have been found in the surface sediments from the Danish coast bordering the Kattegat (Ellegaard *et al.*, 1993),” but they say they “do not know if *G. catenatum* has lived as a small part of the plankton since the ‘Little Ice Age,’ or if the species has been re-introduced by the current system or via ships’ ballast tanks.” And they note “there is also a possibility that the species has become re-established in conjunction with global warming during the past 80 years.” The AD 1996 abundance of the key dinoflagellate was nowhere near that of the “massive blooms” of the Medieval Warm Period. Hence, we date the MWP in

the Kattegat region of the North Sea to the period AD 1200–1400, concluding the peak warmth of the MWP was greater than that of the CWP so far.

Keigwin (1996) noted “it is important to document natural climate variability in order to understand the effects of anthropogenic forcing.” Working with two subcores of a sediment box core retrieved from 33°41.6'N, 57°36.7'W of the undulating plateau of the northeast Bermuda Rise, he measured the oxygen isotope ratios ($\delta^{18}\text{O}$) of the white variety of the planktonic foraminifera *Globigerinoides ruber*, which lives year-round in the upper 25 meters of the northern Sargasso Sea and has a relatively constant annual mass flux and shell flux to the sediments. Calibrating these data against temperature and salinity data obtained at Ocean Station “S” (32°N, 62°30'W) over the prior 42 years, he determined “temperature accounts for about two-thirds of the isotopic signal, whereas salinity accounts for one-third.” He then calculated sea surface temperatures (SSTs) of the prior three millennia, after which he “stacked the temperature proxy data from the two subcores by averaging results in 50-year bins,” obtaining the results shown in Figure 4.2.4.8.2.1.

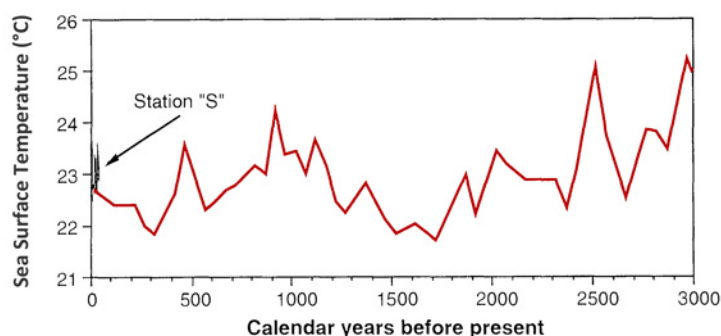


Figure 4.2.4.8.2.1. Fifty-year averages of mean annual sea surface temperature calculated from the $\delta^{18}\text{O}$ data of the two Bermuda Rise sediment subcores, together with the mean annual SSTs measured at Ocean Station “S” over the period 1954–1996. Adapted from Keigwin, L. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* 274: 1504–1508.

As can be seen from this figure, and as Keigwin stated, the northern Sargasso Sea SST “was ~1°C cooler than today ~400 years ago (the Little Ice Age) and 1700 years ago [the Dark Ages Cold Period], and ~1°C warmer than today 1000 years ago (the Medieval Warm Period).” He notes “over the course

Observations: Temperature Records

of three millennia, the range of SST variability in the Sargasso Sea is on the order of twice that measured over recent decades” and concludes “at least some of the warming since the Little Ice Age appears to be part of a natural oscillation.” In addition, “because the changes described here for surface waters over the Bermuda Rise are probably typical of a large part of the western Sargasso Sea, they most likely reflect climate change on the basin or hemispheric scale.”

Andren *et al.* (2000) conducted an extensive analysis of changes over time in siliceous microfossil assemblages and chemical characteristics of various materials found in a well-dated sediment core obtained from the Bornholm Basin in the southwestern Baltic Sea. The data revealed the existence of a period of high primary production at approximately AD 1050. In addition, the diatoms they identified were warm water species such as *Pseudosolenia calcar-avis*, which they describe as “a common tropical and subtropical marine planktonic species” that “cannot be found in the present Baltic Sea.” They also note what they call the Recent Baltic Sea Stage, which began about AD 1200, started at a point when there was “a major decrease in warm water taxa in the diatom assemblage and an increase in cold water taxa, indicating a shift towards a colder climate,” which they associate with the Little Ice Age.

These data clearly indicate there was a period of time in the early part of the past millennium when the climate in the area of the southwestern Baltic Sea was significantly warmer than it is today, as the sediment record of that time and location contained several warm water species of diatoms, some of which can no longer be found there. This period of higher temperatures, in the words of the three researchers, fell within “a period of early Medieval warmth dated to AD 1000–1100,” which “corresponds to the time when the Vikings succeeded in colonizing Iceland and Greenland.” This period was one of strikingly high oceanic primary productivity, demonstrating what seems to be the case with both ecosystems and human societies; i.e., warmer is better.

Keigwin and Boyle (2000) discussed the evidence for a climate oscillation with a return period of 1,500 to 2,000 years that is evident in proxy climate data pertaining to the last deglaciation and has continued (with reduced amplitude) through the Holocene, along with its association with contemporaneous changes—demonstrable for the last deglaciation but tenuous for the Holocene—in the thermohaline circulation of the North Atlantic Ocean. The Little Ice Age was the most recent cold phase of this persistent climatic

phenomenon that may be induced by variations in the production rate of North Atlantic Deep Water. As the two researchers report, “mounting evidence indicates that the LIA was a global event, and that its onset was synchronous within a few years in both Greenland and Antarctica.” In the Northern Hemisphere, for example, they state, it was expressed as a 1°C cooling between approximately 1500 and 1900 AD, with a cooling of approximately 1.7°C in Greenland.

Although the immediate cause or causes of the phenomenon have yet to be definitively identified, there is little question that Earth’s climate oscillates globally on a millennial time-scale independent of the activities of man, and the most recent cold phase of that natural oscillation was what we call the Little Ice Age, centered on approximately AD 1700 and lasting until about AD 1900. Thus it was only to be expected that temperatures would have risen over the past century or so, and they may continue to rise even further until a warm epoch analogous to the Medieval Warm Period is reached. It is unjustified to conclude, as the IPCC does, that the majority of any warming that may currently be occurring is due to anthropogenic CO₂ emissions.

Linsley *et al.* (2000) retrieved a core of continuous coral from a massive colony of *Porites lutea* on the southwest side of Rarotonga in the Cook Islands, within which they measured Sr/Ca ratios on 1-mm sections spanning the entire core (representing 271 years of growth), as well as $\delta^{18}\text{O}$ values at the same resolution from 1726 to 1770 and from 1950 to 1997. The latter interval was used for calibration purposes and utilized Integrated Global Ocean Service System Products SST data. This analysis revealed a quarter-century period centered on about the year 1745 when SSTs in the vicinity of Rarotonga were at least 1.5°C warmer than they are today.

Winter *et al.* (2000) determined SSTs for the periods 1700–1705, 1780–1785, and 1810–1815 from a study of oxygen isotope data obtained from coral skeletons of *Montastrea faveolata* located on the southwestern shore of Puerto Rico. Similar isotope data obtained for the period 1983–1989 and contemporary SSTs directly measured at the University of Puerto Rico’s marine station at La Parguera were used to calibrate the temperature reconstruction technique and provide a current baseline against which to compare the researchers’ Little Ice Age results. The SSTs they derived were significantly cooler during the three Little Ice Age periods than they were at the time of their study. They report their results indicate “the Caribbean

experienced cooling during the Little Ice Age with temperature estimated to be at least 2°–3° cooler than found during the present decade.”

The data presented by Winter *et al.*, as well as the data contained in several papers they cite, led them to conclude “the Little Ice Age may have been more global in extent than previously expected.” It also may have been much colder than previously believed, for they point out the cooling suggested by their data “represents about half of the sea surface temperature cooling recorded in Barbados corals during the Last Glacial Maximum.”

Doose-Rolinski *et al.* (2001) analyzed a complete and annually laminated sediment core extracted from the bed of the northeastern Arabian Sea just south southeast of Karachi, Pakistan, using oxygen isotopes of planktonic foraminifera and measurements of long-chain alkenones to derive a detailed sea surface temperature and evaporation history of the area. They found the greatest temperature fluctuations of the 5,000-year record occurred between 4,600 and 3,300 years ago and between 500 and 200 years ago, which were also the coldest periods of the record. Of the latter interval, they note, “in northern and central Europe this period is known as the ‘Little Ice Age.’” They state their results confirm the “global effects” of this unique climatic change. Also apparent in their temperature history is a period of sustained warmth that prevailed between about 1,250 and 950 years ago, corresponding with the Medieval Warm Period of northern and central Europe.

de Garidel-Thoron and Beaufort (2001) reconstructed a 200,000-year history of primary productivity (PP) in the Sulu Sea north of Borneo, based on abundances of the coccolithophore *Florispheera profunda*, which was measured in a 36-meter giant piston core retrieved from a depth of 3,600 meters. Three time-slices were explored in detail in order to determine high-frequency cycles in the PP record: one from 160 to 130 ka, one from 60 to 30 ka, and one from 22 to 4.1 ka. The finest-scale repeatable feature observed in all three time-slices was a climate-driven PP oscillation with a mean period of approximately 1,500 years.

The two researchers state they cycle’s occurrence in the three different time-slices suggests “a common origin and an almost stationary signal across different climatic conditions.” They also note the PP cycle’s similarity to the 1,470-year temperature cycle observed by Dansgaard *et al.* (1984) in the Camp Century $\delta^{18}\text{O}$ ice core record, the ~1500-year $\delta^{18}\text{O}$ and chemical markers cycles observed by Mayewski

et al. (1997) in the Summit ice core, the 1,470-year climate cycle found by Bond *et al.* (1997, 2001) in North Atlantic deep-sea cores, and the 1500-year climate cycle found by Campbell *et al.* (1998) in an Alaskan lake. These observations led them to suggest there was “a common origin” for the documented cyclicity in the climate of both high and low latitudes.

Hendy *et al.* (2002) reconstructed a 420-year SST history based on Sr/Ca measurements of several coral cores taken from massive *Porites* colonies in the central portion of Australia’s Great Barrier Reef. The earliest portion of this region’s reconstructed temperature history, from 1565 to about 1700, corresponds to the coldest period of the Little Ice Age as recorded in the Northern Hemisphere. Five-year blocks of mean Great Barrier Reef SSTs during this cold period were sometimes 0.5 to 1.0°C or more below the region’s long-term mean. Over the following century, however, South Pacific SSTs were much warmer, as were temperatures in the Northern Hemisphere. In the South Pacific, in fact, SSTs during this period were consistently as warm as—and many times even warmer than—those of the early 1980s, where the coral record ended. During the late 1800s, the South Pacific once again experienced colder conditions that coincided with the “last gasp” of the Little Ice Age in the Northern Hemisphere, after which the Current Warm Period made its presence felt in both regions. That Hendy *et al.* found mid-eighteenth century South Pacific SSTs to be as warm as or even warmer than the final years of the twentieth century suggests the climate of the modern world is in no way unusual, unnatural, or unprecedented.

The mid-eighteenth century warmth of the tropical and subtropical South Pacific Ocean occurred at essentially the same time as the significant peak in Northern Hemispheric temperature that is strikingly evident in the data of Jones *et al.* (1998) and reproduced in the paper of Hendy *et al.* Thus if the data of Hendy *et al.* and Linsley *et al.* (2000 cited earlier) are representative of the great expanse of Southern Hemispheric ocean, the mid-eighteenth century mean temperature of the entire globe may have been about the same as it is now.

Roncaglia (2004) analyzed variations in organic matter deposition from approximately 6,350 cal yr BC to AD 1,430 in a sediment core extracted from the Skalafjord, southern Eysturoy, Faroe Islands to assess climatic conditions in that part of the North Atlantic in the mid- to late-Holocene. She discovered an increase in structured brown phytoclasts, plant tissue,

Observations: Temperature Records

and sporomorphs in sediments dating to ca. AD 830–1090, which she considered indicative of “increased terrestrial influx and inland vegetation supporting the idea of improved climatic conditions.” In addition, she reports high “total dinoflagellate cyst concentration and increased absolute amount of loricae of tintinnid and planktonic crustacean eggs occurred at ca. AD 830–1090.” She concludes these observations “may suggest increased primary productivity in the waters of the fjord,” citing Lewis *et al.* (1990) and Sangiorgi *et al.* (2002). She reports the “amelioration of climate conditions” that promoted the enhanced productivity of both land and sea at this time “may encompass the Medieval Warm Period in the Faroe region.”

Providing a longer and different proxy temperature record from the Northern Hemisphere, Jacoby *et al.* (2004) extracted cores from century-old oak trees growing within one km of the Pacific Ocean on Kunashir Island (the southernmost large island in the Kurile Island chain belonging to Russia, located between the Sea of Okhotsk and the northwest Pacific Ocean) and developed them into a four-century tree-ring width index series that was correlated strongly with island summer air temperature. The scientists report, “the recorded temperature data and the tree-ring data show similar correlation patterns with sea-surface temperatures of the North Pacific.” They found “the tree-ring series explains more than 33% of the variance of the July–September Pacific Decadal Oscillation and has similar spectral properties, further supporting the concept of multidecadal variation or shifts in North Pacific climate, for four centuries.”

The Kunashir June–September mean maximum temperature reconstruction exhibited no long-term trend (neither cooling nor warming) over the entire period from 1600 to 2000, nor did it show any net temperature change over the twentieth century. The peak warmth of the past hundred years occurred right at the mid-century mark, after which temperatures decreased considerably and ended up right about where they started the century.

Lund and Curry (2004) write, “while the Florida Current-Gulf Stream system is arguably one of the most studied features in modern oceanography, almost nothing is known about its behavior on centennial to millennial timescales.” Two researchers analyzed planktonic foraminiferal $\delta^{18}\text{O}$ time series obtained from three well-dated sediment cores retrieved from the seabed near the Florida Keys (24.4°N, 83.3°W) that covered the past 5,200 years. They report the isotopic data from the three cores

indicate “the surface Florida Current was denser (colder, saltier or both) during the Little Ice Age than either the Medieval Warm Period or today,” and “when considered with other published results (Keigwin, 1996; deMenocal *et al.*, 2000), it is possible that the entire subtropical gyre of the North Atlantic cooled during the Little Ice Age ... perhaps consistent with the simulated effects of reduced solar irradiance (Rind and Overpeck, 1993; Shindell *et al.*, 2001).” In addition, they note, “the coherence and phasing of atmospheric ^{14}C production and Florida Current $\delta^{18}\text{O}$ during the Late Holocene implies that solar variability may influence Florida Current surface density at frequencies between 1/300 and 1/100 years.” This evidence confirms centennial- and millennial-scale climatic variability is explained by similar-scale variability in solar activity, much as Bond *et al.* (2001) found for ice-rafting variability in the subpolar North Atlantic, further suggesting there is no need to use the historical increase in the air’s CO_2 content to explain the increase in temperature that marked Earth’s transition from the Little Ice Age to the Current Warm Period.

Asami *et al.* (2005) developed a 213-year (1787–2000) monthly resolved time series of carbon and oxygen isotope data obtained from a coral core retrieved from a *Porites labata* colony located on the northwestern coast of Guam, where the colony had been exposed to open sea surface conditions over the entire period of its development. They determined “the early 19th century (1801–1820) was the coolest in the past 210 years, which is consistent with sea surface temperature [SST] reconstructions derived from a $\delta^{18}\text{O}$ coral record from New Caledonia (Crowley *et al.*, 1997).” This period, they write, “was characterized by a decrease in solar irradiance (Lean *et al.*, 1995; Crowley and Kim, 1996) and by a series of large volcanic eruptions in 1808–1809 and 1818–1822 (Crowley *et al.*, 1997).” From that point on, they report, “the long-term $\delta^{18}\text{O}$ coral trend is characterized by its overall depletion throughout the period,” indicative of a gradual warming of approximately 0.75°C.

This temperature history from a tropical region of the globe is essentially identical to the extratropical Northern Hemispheric temperature record of Esper *et al.* (2002), which stands in stark contrast to temperature reconstructions of Mann *et al.* (1998, 1999), which do not depict the existence of the Little Ice Age. The latter multi-century cool period is clearly manifest at the beginning of the Guam record, and it is evident at about the same time in the New

Caledonia record. The Guam SST history also differs from the Mann *et al.* temperature history depicting close to continuous warming from about 1815, just as the Esper *et al.* record does, whereas the Mann *et al.* record does not depict any warming until after 1910, about a century later. The 0.75°C rise in temperature from the start of the warming until the end of the twentieth century observed in the Guam record is not at all unusual, since it begins at one of the coldest points of the coldest multi-century period of the entire Holocene, the current inter-glacial.

Dima *et al.* (2005) note previous investigations of a Rarotonga coral-based SST reconstruction from the Cook Islands in the South Pacific Ocean focused on documenting and interpreting decadal and interdecadal variability without separating distinct modes of variability within this frequency band (Linsley *et al.* 2000, 2004; Evans *et al.* 2001). They reanalyzed the original coral record using Singular Spectrum Analysis to determine the dominant periods of multi-decadal variability in the series over the period 1727–1996. Their analysis revealed two dominant multi-decadal cycles, with periods of about 25 and 80 years. These modes of variability were found to be similar to multi-decadal modes observed in the global SST field of Kaplan *et al.* (1998) for the period 1856–1996. The ~25-year cycle was found to be associated with the Pacific Decadal Oscillation, whereas the ~80-year cycle was determined to be “almost identical” to a pattern of solar forcing found by Lohmann *et al.* (2004), which, according to Dima *et al.*, “points to a possible solar origin” of this mode of SST variability. The results of their study provide an intriguing glimpse into the cyclical world of oceanic climatic change, demonstrating the existence of two strong multi-decadal modes of SST variability that are clearly natural in origin. Before SST trends can be attributed to anthropogenic activities, they must have all known modes of natural variability removed from them.

Newton *et al.* (2006) analyzed a sediment core collected at 5°12.07'S, 117°29.20'E in the Indo-

Pacific Warm Pool (one of the warmest regions in the modern oceans) for planktonic foraminiferal (*Globigerinoides ruber*) Mg/Ca and $\delta^{18}\text{O}$ data to derive high-resolution summer sea surface temperature (SST) and salinity histories extending back about a thousand years. They report, “the warmest temperatures and highest salinities occurred during the Medieval Warm Period,” which lasted from about AD 1020 to 1260. Over this period, summer SSTs averaged about 29.7°C, as best as can be determined from their graph of the data (Figure 4.2.4.8.2.2), with a peak of about 30.9°C in the vicinity of AD 1080. These values are to be compared with the region’s average modern summer SST of 29.0°C, significantly lower than that of the Medieval Warm Period. They also found “the coolest temperatures and lowest salinities occurred during the Little Ice Age,” the

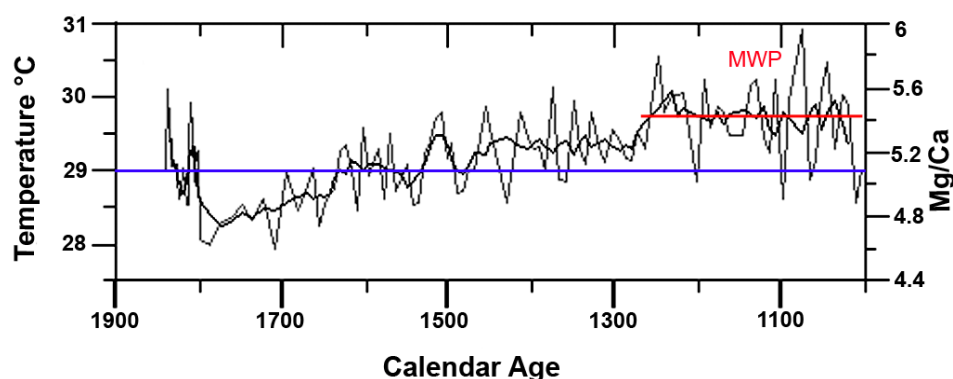


Figure 4.2.4.8.2.2. Mg/Ca-derived summer sea surface temperatures (SST) in the Indo-Pacific Warm Pool. The blue line represents the modern average SST value of 29°C. Adapted from Newton, A., Thunell, R., and Stott, L. 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters* 33: 10.1029/2006GL027234.

lowest temperatures of which occurred “around AD 1700, during the period of reduced solar intensity known as the Maunder Minimum,” when summer SSTs “were 1.0–1.5°C cooler than present,” presumably due to the lower solar activity of that period. Newton *et al.* state their data from the Makassar Strait of Indonesia clearly indicates “climate changes during the Medieval Warm Period and Little Ice Age were not confined to the high latitudes” nor to countries bordering the North Atlantic Ocean.

Richey *et al.* (2007) note the variability of the hemispheric temperature reconstructions of Mann and Jones (2003) over the past one to two thousand years

Observations: Temperature Records

were “subdued ($\leq 0.5^{\circ}\text{C}$)” and their low-amplitude reconstructions contrast “with several individual marine records that indicate that centennial-scale sea surface temperature (SST) oscillations of $2\text{--}3^{\circ}\text{C}$ occurred during the past 1-2 k.y. (i.e., Keigwin, 1996; Watanabe *et al.*, 2001; Lund and Curry, 2006; Newton *et al.*, 2006).” They also contrast with “tree-ring and multiproxy reconstructions designed to capture multicentennial-scale variability (e.g., Esper *et al.*, 2002; Moberg *et al.*, 2005),” which further suggests “the amplitude of natural climate variability over the past 1 k.y. is $>0.5^{\circ}\text{C}$,” the scientists state. They constructed a continuous decadal-scale-resolution record of climate variability over the past 1,400 years in the northern Gulf of Mexico from a box core recovered in the Pigmy Basin, northern Gulf of Mexico ($27^{\circ}11.61'\text{N}$, $91^{\circ}24.54'\text{W}$), based on climate proxies derived from paired analyses of Mg/Ca and $\delta^{18}\text{O}$ in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages.

The four researchers report two multi-decadal intervals of sustained high Mg/Ca indicated Gulf of Mexico sea surface temperatures (SSTs) were as warm as, or warmer than, near-modern conditions between 1,000 and 1,400 yr BP (during the MWP), and foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr BP) indicated SSTs were $2\text{--}2.5^{\circ}\text{C}$ below modern SSTs. In addition, they found the four minima in the Mg/Ca record between 900 and 250 yr. B.P. corresponded in time with the Maunder, Sporer, Wolf, and Oort sunspot minima.

Barron and Bukry (2007) developed high-resolution records of diatoms and silicoflagellate assemblages spanning the past 2,000 years, from analyses of a sediment core extracted from the Carmen ($26^{\circ}17.39'\text{N}$, $109^{\circ}55.24'\text{W}$), Guaymas (27.92°N , 111.61°W), and Pescadero Basins ($24^{\circ}16.78'\text{N}$, $108^{\circ}11.65'\text{W}$) of the Gulf of California. The relative abundance of *Azpeitia nodulifera*, a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures, was found to be far greater during the Medieval Warm Period than at any other time in the 2,000-year period studied. During the Current Warm Period, its relative abundance was lower than the 2,000-year mean.

Matul *et al.* (2007) studied the distributions of different species of siliceous microflora (diatoms), calcareous microfauna (foraminifers), and spore-pollen assemblages in sediment cores retrieved from 21 sites on the inner shelf of the southern and eastern

Laptev Sea, starting from the Lena River delta and moving seaward between about 130 and 134°E and stretching from approximately 71 to 78°N . The cores were acquired by a Russian-French Expedition during the cruise of R/V *Yakov Smirnitsky* in 1991. The analysis indicated the existence of “the Medieval Warm Period, $\sim 600\text{--}1100$ years BP; the Little Ice Age, $\sim 100\text{--}600$ years BP, with the cooling maximum, $\sim 150\text{--}450$ years BP, and the ‘industrial’ warming during the last 100 years.” In addition, “judging from the increased diversity and abundance of the benthic foraminifers, the appearance of moderately thermophilic diatom species, and the presence of forest tundra (instead of tundra) pollen,” they conclude, “the Medieval warming exceeded the recent ‘industrial’ one.”

Using a well-established radiolarian-based transfer function, Fengming *et al.* (2008) developed a mean annual sea surface temperature (SST) history of the last 10,500 years based on data derived from the top 390 cm of a gravity core recovered from the western slope of the northern Okinawa Trough ($29^{\circ}13.93'\text{N}$, $128^{\circ}53'\text{E}$) of the East China Sea. This record revealed that early in the Holocene, between 10,500 and 8,500 calendar years before present (cal. yr BP), mean annual SST gradually rose from ~ 23.5 to $\sim 25.2^{\circ}\text{C}$, but it then declined abruptly to $\sim 24.0^{\circ}\text{C}$ at about 8,200 cal. yr BP. The middle portion of the Holocene that followed was relatively stable, with a mean SST of $\sim 24.7^{\circ}\text{C}$, after which a dramatic cooling to $\sim 23.6^{\circ}\text{C}$ occurred at about 3,100 cal. yr BP that lasted until about 2,600 cal. yr BP, largely coincident with what is known as the “third Neoglaciation” of Europe.

This cold interval was followed by the Roman Warm Period ($\sim 2,600\text{--}1,700$ cal. yr BP), when SSTs rose to $\sim 24.8^{\circ}\text{C}$. Then came the Dark Ages Cold Period, when SSTs dropped to $\sim 23.8^{\circ}\text{C}$, after which temperatures during the Medieval Warm Period ($\sim 1,250\text{--}750$ cal. yr BP) returned to $\sim 24.8^{\circ}\text{C}$, only to decline to $\sim 24.2^{\circ}\text{C}$ during the Little Ice Age ($\sim 600\text{--}300$ cal. yr BP). Thereafter, it began to warm once again, but the warming was short-lived, with the temperature reversing course and falling slightly below the Little Ice Age minimum value of $\sim 24.2^{\circ}\text{C}$ at about AD 1950, where the SST history terminates.

This SST record from the East China Sea clearly reveals the millennial-scale cycling of climate seen in numerous paleoclimatic proxies throughout the world (see Figure 4.2.4.8.2.3), and it suggests the near-identical peak SSTs of the East China Sea during both the Medieval and Roman Warm Periods were

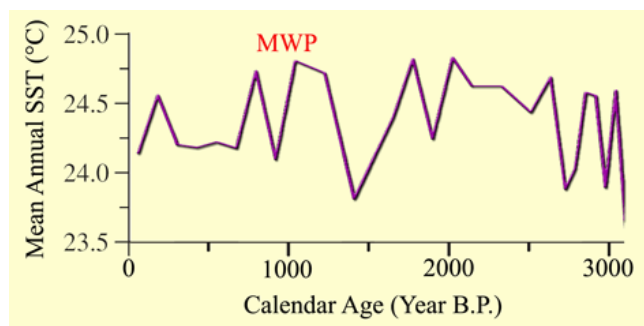


Figure 4.2.4.8.2.3. Sea surface temperature proxy derived from a gravity core recovered from the East China Sea. Adapted from Fengming, C., Tiegang, L., Lihua, Z., and Jun, Y. 2008. A Holocene paleotemperature record based on radiolaria from the northern Okinawa Trough (East China Sea). *Quaternary International* **183**: 115–122.

probably significantly greater than those of today, which likely have had insufficient time to reverse course and warm to such an elevated level from their lowest level of the past 1,300 years.

In reference to the claims of Jansen *et al.* (2007) and Mann *et al.* (2008) that Northern Hemisphere surface temperature reconstructions indicate “the late twentieth century was warmer than any other time during the past 500 years and possibly any time during the past 1,300 years,” Oppo *et al.* (2009) state these temperature reconstructions may not be as representative of the planet as a whole as they are typically made out to be, because they “are based largely on terrestrial records from extra-tropical or high-elevation sites,” whereas “global average surface temperature changes closely follow those of the global tropics, which are 75% ocean.” The three researchers derived a “continuous sea surface temperature (SST) reconstruction from the IPWP [Indo-Pacific Warm Pool],” which they describe as “the largest reservoir of warm surface water on the Earth and the main source of heat for the global atmosphere.” This temperature history, based on $\delta^{18}\text{O}$ and Mg/Ca data obtained from samples of the planktonic foraminifera *Globigerinoides ruber* found in two gravity cores, a nearby multi-core (all at 3°53’S, 119°27’E), and a piston core (at 5°12’S, 117°29’E) recovered from the Makassar Strait on the

Sulawesi margin, spans the past two millennia (see Figure 4.2.4.8.2.4) and “overlaps the instrumental record, enabling both a direct comparison of proxy data to the instrumental record and an evaluation of past changes in the context of twentieth century trends.”

They report the SST reconstruction “shows cooler temperatures between about AD 400 and AD 950 [the Dark Ages Cold Period] than during much of the so-called Medieval Warm Period (about AD 900–1300).” Of the latter period, they state, “reconstructed SSTs were warmest from AD 1000 to AD 1250,” when “SSTs within error of modern SSTs occurred in the IPWP,” as also was the case “during brief periods of the first millennium AD,” during the Roman Warm Period. Thus a globally significant SST history, “enabling both a direct comparison of proxy data to the instrumental record and an evaluation of past

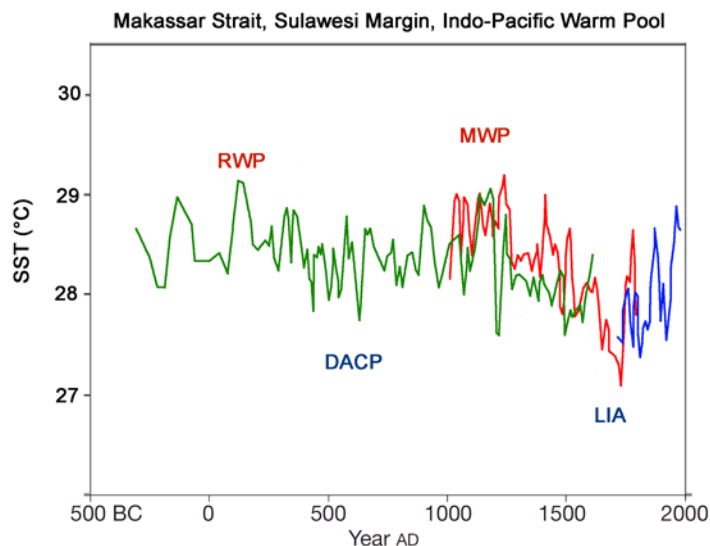


Figure 4.2.4.8.2.4. A 2,000-year temperature history, based on $\delta^{18}\text{O}$ and Mg/Ca data obtained from samples of a planktonic foraminifera found in ocean sediment cores recovered from the Makassar Strait on the Sulawesi margin of the Indo-Pacific Warm Pool. Adapted from Oppo, D.W., Rosenthal, Y., and Linsley, B.K. 2009. 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature* **460**: 1113–1116.

changes in the context of twentieth century trends,” shows substantial evidence that throughout portions of both the Roman and Medieval Warm Periods, SSTs in the Indo-Pacific Warm Pool were essentially equivalent to those of “the late twentieth century,” once again indicating current air temperatures in this critically important region of the globe are not out of

Observations: Temperature Records

the ordinary.

Isono *et al.* (2009) studied three sediment cores retrieved off the coast of central Japan in the northwestern Pacific Ocean (36°02'N, 141°47'E) to generate a multi-decadal-resolution record of alkenone-derived sea surface temperature (SST) that covers the full expanse of the Holocene. This record, they write, “showed centennial and millennial variability with an amplitude of ~1°C throughout the entire Holocene,” and they state, “spectral analysis for SST variation revealed a statistically significant peak with 1470-year periodicity.” At the end of the record, Isono *et al.* report, “SST minima centered at ca. 0.3 ka and ca. 1.5 ka are correlated with the Little Ice Age and the Dark Ages Cold Period in Europe, respectively, whereas the SST maximum centered at ca. 1.0 ka is correlated with the Medieval Warm Period.” From data presented in the authors’ Figure 2, it can be estimated the MWP was about 1°C warmer than the Current Warm Period.

Li *et al.* (2009) analyzed a sediment core extracted from the northern East China Sea (31.68°N, 125.81°E) in June 2006, employing the alkenone paleotemperature index U^k_{37} together with the Muller *et al.* (1998) calibration equation to construct a sea surface temperature history of that region covering the past 3,600 years (Figure 4.2.4.8.2.5). They report “the highest temperature was 22.7°C which was recorded at 1.01 cal ka BP,” about three-fifths of the way through the Medieval Warm Period. They also note cooling prevailed “from 0.85 cal. ka BP to present,” with the latter point indicating a temperature of 19.78°C. We calculate, based on their work, the peak warmth of the MWP was 2.9°C greater than the mean warmth of the first decade of the twenty-first century, which is often characterized as the warmest decade of the instrumental period.

Richter *et al.* (2009) obtained high-resolution (22-year average) planktonic foraminiferal Mg/Ca and stable oxygen isotope ($\delta^{18}O$) data from a pair of sediment cores retrieved from the northeast Atlantic Ocean’s Feni Drift, Rockall Trough region (55°39.02'N, 13°59.10'W and 55°39.10'N, 13°59.13'W), from which they derived late Holocene (0–2.4 ka BP) sea surface temperatures (SSTs). These data revealed “a general long-term cooling trend,” but “superimposed on this overall trend” were “partly

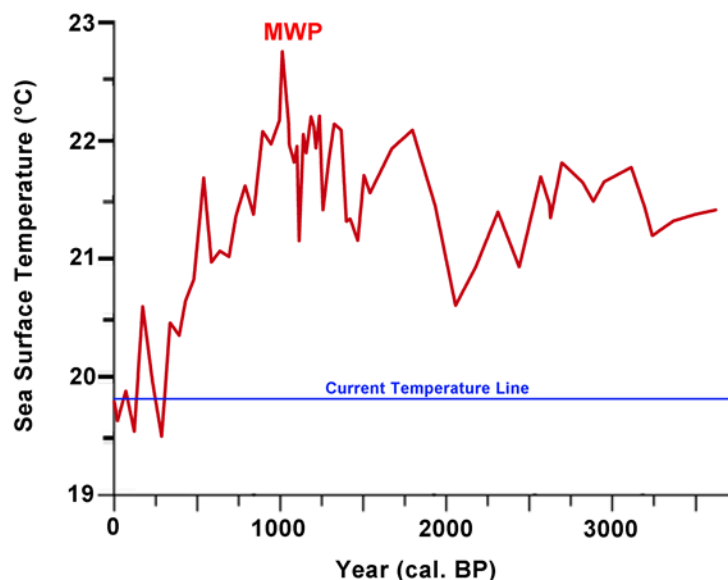


Figure 4.2.4.8.2.5. A 3,600-year proxy sea surface temperature record from the northern East China Sea. Adapted from Li, G.X., Sun, X.Y., Liu, Y., Bickert, T., and Ma, Y.Y. 2009. Sea surface temperature record from the north of the East China Sea since late Holocene. *Chinese Science Bulletin* 54: 4507–4513.

higher temperatures and salinities from 180 to 560 AD and 750–1160 AD,” which the three researchers say “may be ascribed to the Roman and Medieval Warm Periods, respectively.” The latter was followed by the Little Ice Age (LIA) and what they describe as the “post-LIA recovery and, possibly, (late) 20th century anthropogenic warming.”

The twentieth century warming, they write, “concurs with distinct continental-scale warming, consistently reaching unprecedented maximum temperatures after ~1990 AD.” Their use of the word “unprecedented” is a bit misleading, for they subsequently write, “the SST increase over the last three decades does not, or not ‘yet’, appear unusual compared to the entire 0–2.4 ka record,” and “the warming trend over the second half of the 20th century has not yet reverted the late Holocene millennial-scale cooling.” Their data clearly indicate the peak temperature of the Medieval Warm Period was approximately 2.2°C greater than the peak temperature of the late twentieth century, and the peak temperature of the Roman Warm Period was about 2.7°C greater than that of the late twentieth century.

That the warmest portions of the Roman and Medieval Warm Periods in the vicinity of the

northeast Atlantic were so much warmer than the warmest of the Current Warm Period, and at times when the air's CO₂ content was much less than it is currently, strongly suggests the atmosphere's CO₂ concentration had little or no impact on the late-Holocene climatic history of that part of the planet. The three Dutch researchers state, "pervasive multidecadal- to centennial-scale variability throughout the sedimentary proxy records can be partly attributed to solar forcing and/or variable heat extraction from the surface ocean caused by shifts in the prevailing state of the North Atlantic Oscillation," as well as to "internal (unforced) fluctuations."

Sejrup *et al.* (2010) developed a 1,000-year-long proxy temperature record from two sediment cores extracted from the seabed of the eastern Norwegian Sea (~64°N, 3°E), "based on measurements of $\delta^{18}\text{O}$ in *Neogloboquadrina pachyderma*, a planktonic foraminifer that calcifies at relatively shallow depths within the Atlantic waters of the eastern Norwegian Sea during late summer." They found "the lowest isotope values (highest temperatures) of the last millennium are seen ~1100–1300 A.D., during the Medieval Climate Anomaly, and again after ~1950 A.D." By applying "relatively conservative isotopic estimates of temperature change" utilized by the authors of -0.25‰/°C, from the graphs of their data, it can be estimated the most extreme minimum $\delta^{18}\text{O}$ values of the 1100–1300 period yield temperatures at least 0.35°C warmer than those of the post-1950 period (see Figure 4.2.4.8.2.6).

Combining use of ²¹⁰Pb dates, identification of Icelandic tephra of known age, and wiggle matching of ¹⁴C radiocarbon dates, Sejrup *et al.* (2011) established exceptionally accurate chronologies for two marine sediment cores raised from the same location on the Norwegian continental margin (63°45'44"N, 05°15'19"E) in 1998. They evaluated $\delta^{18}\text{O}$ values of the planktonic foram *Neogloboquadrina pachyderma* (dex), a parameter influenced by the temperature and salinity of the seawater in which the foram lives, over the 8,000-year period spanned by the retrieved cores. After noting the work of Berstad *et al.* (2003) suggests salinity should have a relatively small influence on the isotope values of *N. Pachy.* (dex) at the site of their study, they developed the $\delta^{18}\text{O}$ history depicted in Figure 4.2.4.8.2.7, which they use as a proxy for what they

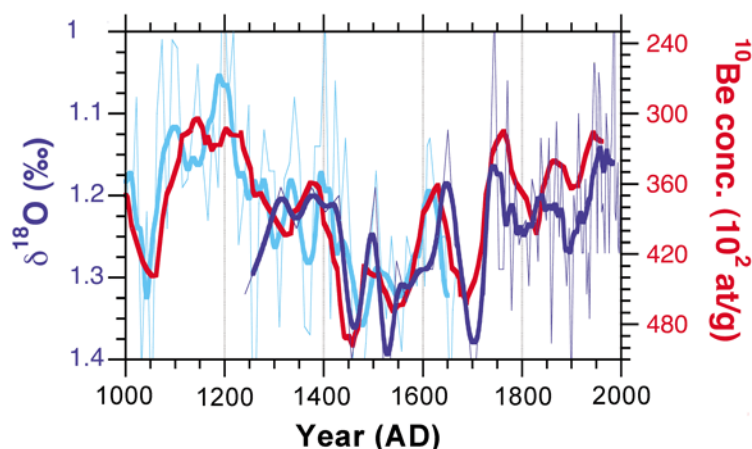


Figure 4.2.4.8.2.6. A 1,000-year proxy temperature record based on measurements of $\delta^{18}\text{O}$ in a planktonic foraminifer obtained from two sediment cores in the eastern Norwegian Sea. Adapted from Sejrup, H.P., Lehman, S.J., Hafliðason, H., Noone, D., Muscheler, R., Berstad, I.M., and Andrews, J.T. 2010. Response of Norwegian Sea temperature to solar forcing since 1000 A.D. *Journal of Geophysical Research* **115**: 10.1029/2010JC006264.

call "near surface water summer temperature." This

history clearly shows the peak warmth of the Medieval Warm Period was significantly greater than the peak warmth of the Current Warm Period to date.

Ran *et al.* (2011) reconstructed summer sea surface temperature (SST) on the North Icelandic shelf for the period AD 940–2006, based on high-resolution and precisely dated diatom records and "a modern diatom-environmental dataset from around Iceland ... established as a basis for quantitative reconstruction of palaeoceanographic conditions on the North Icelandic shelf (Jiang *et al.*, 2001, 2002)." The four researchers find the sea surface on the North Icelandic shelf "was not as warm during the last century as during the Medieval Warm Period (MWP)." They also state, "warm and stable conditions with relatively strong influence of the Irminger Current on the North Icelandic shelf are indicated during the interval AD 940–1300, corresponding in time to the MWP," and "a considerable cooling at ~AD 1300 indicates the transition to the Little Ice Age (LIA) with increased influence of Polar and Arctic water masses deriving from the East Greenland and East Icelandic currents." After that came "an extended cooling period between AD 1300 and 1910," followed by "a two-step warming during the last 100 years" that was "interrupted by three cool events around AD 1920, in the AD 1960s and in the late AD 1990s."

Observations: Temperature Records

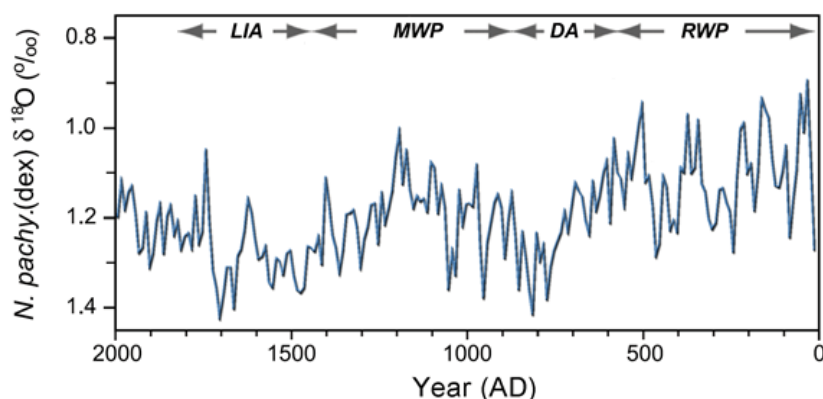


Figure 4.2.4.8.2.7. Proxy temperature reconstruction of *N. pachyderma* (dex) $\delta^{18}\text{O}$ vs. time. Adapted from Sejrup, H.P., Hafliðason, H., and Andrews, J.T. 2011. A Holocene North Atlantic SST record and regional climate variability. *Quaternary Science Reviews* **30**: 3181–3195.

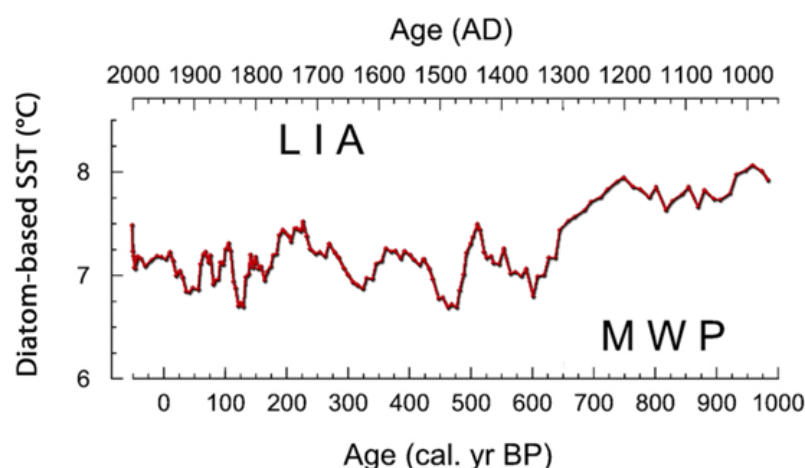


Figure 4.2.4.8.2.8. Reconstructed summer sea surface temperature (SST) on the North Icelandic shelf for the period AD 940–2006. Adapted from Ran, L., Jiang, H., Knudsen, K.L., and Eiriksson, J. 2011. Diatom-based reconstruction of palaeoceanographic changes on the North Icelandic shelf during the last millennium. *Palaeogeography, Palaeoclimatology, Palaeo-ecology* **302**: 109–119.

Ran *et al.* thus present another proxy record indicating the warmth of the more distant past clearly exceeded that of the recent past, with the peak temperature of the MWP exceeding that of the Current Warm Period at this location by about 0.6°C, as best as can be determined from the graphical representation of Ran *et al.*'s data presented in Figure 4.2.4.8.2.8. They conclude, “the data suggest that

solar radiation may be one of the important forcing mechanisms behind the palaeo-oceanographic changes.”

Saenger *et al.* (2011) analyzed seabed sediment sub-cores taken from a giant gravity core (59GGC) and a multicore (MC22) separated from each other by 22 km along the Carolina Slope of the western North Atlantic Ocean near the southern flank of the Gulf Stream at 32.977°N, 76.316°W and 32.784°N, 76.276°W, respectively, developed two sets of 2,000-year sea surface temperature (SST) histories based on Mg/Ca ratios of the shells of the planktic foraminifera *Globigerinoides ruber*, using two Mg/Ca-SST calibrations: that of Anand *et al.* (2003) for both cores and that of Arbuszewski *et al.* (2010) for the 59GGC core only.

Using the calibration of Anand *et al.* (2003), the peak warmth of the MWP is seen to have been about 0.1°C less than that of the CWP based on both the 59GGC and MC22 core data. When using the calibration of Arbuszewski *et al.* (2010), the peak warmth of the MWP is seen to have been about 0.7°C greater than that of the CWP based on the data from the 59GGC core. Thus Saenger *et al.*'s study suggests the peak warmth of the MWP was 0.1°C less than that of the CWP, and it also suggests the peak warmth of the MWP was 0.7°C greater than that of the CWP at the 59GGC site, with the MWP of both sites falling in the range of about AD 700–1300. Whichever calibration creates the more accurate record, it is clear temperatures in the region are hardly

unusual or unnatural.

Copard *et al.* (2012) extracted the rare earth element *neodymium* (Nd) from pristine aragonite fragments of fossil deep-sea corals of the species *Lophelia pertusa* taken by gravity core from the southwestern flank of Rockall Trough in the Northeast Atlantic Ocean (55°31.17'–55°32' N,

15°39.08'–15°40'W). They calculated isotopic composition (ϵNd) according to the relationship $\epsilon\text{Nd} = ([^{143}\text{Nd}/^{144}\text{Nd}]_{\text{sample}}/0.512638) - 1 \times 10,000$, as per Jacobsen and Wasserberg (1980). Copard *et al.* state,

“the warm Medieval Climate Anomaly (1,000–1250 AD) was characterized by low ϵNd values (-13.9 to -14.5) ... while the Little Ice Age (around 1350–1850 AD) was marked by higher ϵNd values.” After the end of the LIA, ϵNd once again declines, but according to the author's Figure 5d, it never quite reaches the -13.9 value that defines the boundary condition ($\epsilon\text{Nd} = -13.9$) of the beginning and end of the MWP. Because the ϵNd value of modern seawater recirculating in the northern North Atlantic at surface and intermediate depths is only -13.1, it can be cautiously concluded ocean temperatures during the Current Warm Period have not eclipsed those experienced during Medieval times.

Wu *et al.* (2012) write, “one of the key questions in the reconstruction of late Holocene climate is whether or not the 20th-century warming is unusual over the past two millennia,” noting “a clear answer to this question is crucial for the assessment of the relative contribution of human activities and natural processes to the observed warming.” They developed a bi-decadal-resolution record of sea surface temperature (SST) in the Southern Okinawa Trough covering the past 2,700 years by analyzing tetraether lipids of planktonic archaea in the ODP Hole 1202B (24°48'N, 122°30'E), which they describe as “a site under the strong influence of the Kuroshio Current and East Asian monsoon.”

The five Chinese researchers report finding SST anomalies that “generally coincided with previously reported late Holocene climate events, including the Roman Warm Period [120 BC–AD 400], Sui-Tang Dynasty Warm Period [AD 550–790], Medieval Warm Period [AD 900–1300], Current Warm Period [AD 1850–present], Dark Age Cold Period [AD 400–550] and Little Ice Age [AD 1300–1850].” They note, “despite an increase since AD 1850, the mean SST in the 20th century is still within the range of natural variability during the past 2700 years.” In addition, they note climate records from East China (Ge *et al.*, 2004), the North Icelandic Shelf (Patterson *et al.*, 2010), and Greenland (Kobashi *et al.*, 2011) also exhibit “centennial-scale warm periods during the first millennia AD, comparable to or even warmer than mean 20th-century conditions.”

Moros *et al.* (2012) inferred late-Holocene trends and variability of the East Greenland Current's influence on the Sub-Arctic Front, based on new

oxygen isotope data of three planktonic foraminiferal species, Mg/Ca-derived sea-surface temperature data, alkenone biomarker paleothermometry, coccolith abundance, species counts, and diatom census data derived from a sediment core extracted from Reykjanes Ridge at 58°56.327'N, 30°24.590'W in the North Atlantic Ocean. They found “increasingly colder millennial-scale cooling events” centered on 5.6, 3.8, 2.7, 1.3, and 0.3 ka, the latter and coldest of which was the Little Ice Age. Between the third and fourth of these cold events was the Roman Warm Period, which they describe as the warmest period of the late Holocene.

Climate change is real. In fact, it's the *norm*. And in the several oceanic studies briefly reviewed above, as well as studies pertaining to the terrestrial surface of the planet reported on elsewhere in this Section 4.2, Earth's climate has been recognized as having shifted over the past century or so from the coldest period of the current interglacial to a significantly warmer state, but one that appears not yet to have achieved the level of warmth characteristic of the prior Medieval Warm Period or the earlier Roman Warm Period. Since none of these warming periods was driven by increases in the air's CO_2 concentration, there is no compelling reason to conclude—especially with the level of certainty expressed by the IPCC—that the twentieth century warming of the globe was driven by concurrent anthropogenic CO_2 emissions.

References

- Anand, P., Elderfield, H., and Conte, M.H. 2003. Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series. *Paleoceanography* **18**: 10.1029/2002PA000846.
- Andren, E., Andren, T., and Sohlenius, G. 2000. The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. *Boreas* **29**: 233–250.
- Arbuszewski, J., deMenocal, P., Kaplan, A., and Farmer, E.C. 2010. On the fidelity of shell-derived $\delta^{18}\text{O}_{\text{seawater}}$ estimates. *Earth and Planetary Science Letters* **300**: 185–196.
- Asami, R., Yamada, T., Iryu, Y., Quinn, T.M., Meyer, C.P., and Paulay, G. 2005. Interannual and decadal variability of the western Pacific sea surface condition for the years 1787–2000: Reconstruction based on stable isotope record from a Guam coral. *Journal of Geophysical Research* **110**: 10.1029/2004JC002555.

Observations: Temperature Records

- Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* **62**: 115–139.
- Berstad, I.M., Sejrup, H.P., Klitgaard-Kristensen, D., and Haflidason H. 2003. Variability in temperature and geometry of the Norwegian Current over the past 600 yr; stable isotope and grain size evidence from the Norwegian margin. *Journal of Quaternary Science* **18**: 591–602.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Bond, G., Showers, W., Chezebiet, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial scale cycle in North-Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Campbell, I.D., Campbell, C., Apps, M.J., Rutter, N.W., and Bush, A.B.G. 1998. Late Holocene ca.1500 yr climatic periodicities and their implications. *Geology* **26**: 471–473.
- Copard, K., Colin, C., Henderson, G.M., Scholten, J., Douville, E., Sicre, M.-A., and Frank, N. 2012. Late Holocene intermediate water variability in the northeastern Atlantic as recorded by deep-sea corals. *Earth and Planetary Science Letters* **313–314**: 34–44.
- Crowley, T.J. and Kim, K.-Y. 1996. Comparison of proxy records of climate change and solar forcing. *Geophysical Research Letters* **23**: 359–362.
- Crowley, T.J., Quinn, T.M., and Taylor, F.W. 1997. Evidence for a volcanic cooling signal in a 335 year coral record from New Caledonia. *Paleoceanography* **12**: 633–639.
- Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, N., Gundestrup, N., and Hammer, C.U. 1984. North Atlantic climatic oscillations revealed by deep Greenland ice cores. In: Hansen, J.E. and Takahashi, T. (Eds.) *Climate Processes and Climate Sensitivity*, American Geophysical Union, Washington, DC, pp. 288–298.
- de Garidel-Thoron, T. and Beaufort, L. 2001. Millennial-scale dynamics of the East Asian winter monsoon during the last 200,000 years. *Paleoceanography* **16**: 1–12.
- deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M. 2000. Coherent high- and low-latitude variability during the Holocene warm period. *Science* **288**: 2198–2202.
- Dima, M., Felis, T., Lohmann, G., and Rimbu, N. 2005. Distinct modes of bidecadal and multidecadal variability in a climate reconstruction of the last centuries from a South Pacific coral. *Climate Dynamics* **25**: 329–336.
- Dooze-Rolinski, H., Rogalla, U., Scheeder, G., Luckge, A., and von Rad, U. 2001. High-resolution temperature and evaporation changes during the late Holocene in the northeastern Arabian Sea. *Paleoceanography* **16**: 358–367.
- Ellegaard, M., Christensen, N.F., and Moestrup, O. 1993. Temperature and salinity effects on growth of a non-chain-forming strain of *Gymnodinium catenatum* (Dinophyceae) established from a cyst from recent sediments in the Sound (Oresund), Denmark. *Journal of Phycology* **29**: 418–426.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Evans, M.N., Cane, M.A., Schrag, D.P., Kaplan, A., Linsley, B.K., Villalba, R., and Wellington, G.M. 2001. Support for tropically-driven Pacific decadal variability based on paleoproxy evidence. *Geophysical Research Letters* **28**: 3689–3692.
- Fengming, C., Tiegang, L., Lihua, Z., and Jun, Y. 2008. A Holocene paleotemperature record based on radiolaria from the northern Okinawa Trough (East China Sea). *Quaternary International* **183**: 115–122.
- Fjellsa, A. and Nordberg, K. 1996. Toxic dinoflagellate “blooms” in the Kattegat, North Sea, during the Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **124**: 87–105.
- Ge, Q.S., Zheng, J.Y., Man, Z.M., Fang, X.Q., and Zhang, P.Y. 2004. Key points on temperature change of the past 2000 years in China. *Progress in Natural Science* **14**: 730–737.
- Hendy, E.J., Gagan, M.K., Alibert, C.A., McCulloch, M.T., Lough, J.M., and Isdale, P.J. 2002. Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. *Science* **295**: 1511–1514.
- Isono, D., Yamamoto, M., Irino, T., Oba, T., Murayama, M., Nakamura, T., and Kawahata, H. 2009. The 1500-year climate oscillation in the midlatitude North Pacific during the Holocene. *Geology* **37**: 591–594.
- Jacobsen, S. and Wasserburg, G. 1980. Sm-Nd isotopic evolution of chondrites. *Earth and Planetary Science Letters* **50**: 139–155.
- Jacoby, G., Solomina, O., Frank, D., Eremenko, N., and D’Arrigo, R. 2004. Kunashir (Kuriles) oak 400-year reconstruction of temperature and relation to the Pacific Decadal Oscillation. *Palaeogeography, Palaeoclimatology, Palaeoecology* **209**: 303–311.
- Jansen, E. et al. 2007. In: Solomon, S. et al. (Eds.) *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge, UK, pp. 466–482.

- Jiang, H., Seidenkrantz, M.-S., Knudsen, K.L., and Eiriksson, J. 2001. Diatom surface sediment assemblages around Iceland and their relationships to oceanic environmental variables. *Marine Micropaleontology* **41**: 73–96.
- Jiang, H., Seidenkrantz, M.-S., Knudsen, K.L., and Eiriksson, J. 2002. Late-Holocene summer sea-surface temperatures based on a diatom record from the North Icelandic shelf. *The Holocene* **12**: 137–147.
- Jones, P.D., Briffa, K.R., Barnett, T.P., and Tett, S.F.B. 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures. *The Holocene* **8**: 455–471.
- Kaplan, A., Cane, M.A., Kushnir, Y., Clement, A.C., Blumenthal, M.B., and Rajagopalan, B. 1998. Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research* **103**: 18,567–18,589.
- Keigwin, L. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.
- Keigwin, L.D. and Boyle, E.A. 2000. Detecting Holocene changes in thermohaline circulation. *Proceedings of the National Academy of Sciences USA* **97**: 1343–1346.
- Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: 10.1029/2011GL049444.
- Lean, J., Beer, J., and Bradley, R. 1995. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Research Letters* **22**: 3195–3198.
- Lewis, J., Dodge, J.D., and Powell, A.J. 1990. Quaternary dinoflagellate cysts from the upwelling system offshore Peru, Hole 686B, ODP Leg 112. In: Suess, E., von Huene, R., et al. (Eds.) *Proceedings of the Ocean Drilling Program, Scientific Results 112*. Ocean Drilling Program, College Station, TX, pp. 323–328.
- Li, G.X., Sun, X.Y., Liu, Y., Bickert, T., and Ma, Y.Y. 2009. Sea surface temperature record from the north of the East China Sea since late Holocene. *Chinese Science Bulletin* **54**: 4507–4513.
- Linsley, B.K., Wellington, G.M., and Schrag, D.P. 2000. Decadal sea surface temperature variability in the subtropical South Pacific from 1726 to 1997 A.D. *Science* **290**: 1145–1148.
- Linsley, B.K., Wellington, G.M., Schrag, D.P., Ren, L., Salinger, M.J., and Tudhope, A.W. 2004. Geochemical evidence from corals for changes in the amplitude and spatial pattern of South Pacific interdecadal climate variability over the last 300 years. *Climate Dynamics* **22**: 1–11.
- Lohmann, G., Rimbu, N., and Dima, M. 2004. Climate signature of solar irradiance variations: analysis of long-term instrumental, historical, and proxy data. *International Journal of Climatology* **24**: 1045–1056.
- Lund, D.C. and Curry, W.B. 2004. Late Holocene variability in Florida Current surface density: Patterns and possible causes. *Paleoceanography* **19**: 10.1029/2004PA001008.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Mann, M.E. and Jones, P.D. 2003. Global surface temperature over the past two millennia. *Geophysical Research Letters* **30**: 1820–1823.
- Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., and Ni, F. 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences, USA* **105**: 13,252–13,257.
- Matul, A.G., Khusid, T.A., Mukhina, V.V., Chekhovskaya, M.P., and Safarova, S.A. 2007. Recent and late Holocene environments on the southeastern shelf of the Laptev Sea as inferred from microfossil data. *Oceanology* **47**: 80–90.
- Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., and Prentice, M. 1997. Major features and forcing of high-latitude Northern Hemisphere atmospheric circulation using a 110,000-year long glaciogeochemical series. *Journal of Geophysical Research* **102**: 26,345–26,366.
- Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.
- Moros, M., Jansen, E., Oppo, D.W., Giraudeau, J., and Kuijpers, A. 2012. Reconstruction of the late-Holocene changes in the Sub-Arctic Front position at the Reykjanes Ridge, north Atlantic. *The Holocene* **22**: 877–886.
- Muller, P.J., Kirt, G., Ruhland, G., von Storch, I., and Rosell-Melé, A. 1998. Calibration of the alkenone paleotemperature index U^k37 based on core-tops from the Eastern South Atlantic and the global ocean (60°N–60°S). *Geochimica et Cosmochimica Acta* **62**: 1757–1772.

Observations: Temperature Records

- Newton, A., Thunell, R., and Stott, L. 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters* **33**: 10.1029/2006GL027234.
- Oppo, D.W., Rosenthal, Y., and Linsley, B.K. 2009. 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature* **460**: 1113–1116.
- Patterson, W.P., Dietrich, K.A., Holmden, C., and Andrews, J.T. 2010. Two millennia of North Atlantic seasonality and implications for Norse colonies. *Proceedings of the National Academy of Sciences USA* **107**: 5306–5310.
- Ran, L., Jiang, H., Knudsen, K.L., and Eiriksson, J. 2011. Diatom-based reconstruction of palaeoceanographic changes on the North Icelandic shelf during the last millennium. *Palaeogeography, Palaeoclimatology, Palaeoecology* **302**: 109–119.
- Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.
- Richter, T.O., Peeters, F.J.C., and van Weering, T.C.E. 2009. Late Holocene (0–2.4 ka BP) surface water temperature and salinity variability, Feni Drift, NE Atlantic Ocean. *Quaternary Science Reviews* **28**: 1941–1955.
- Rind, D. and Overpeck, J. 1993. Hypothesized causes of decade- to century-scale climate variability: Climate model results. *Quaternary Science Reviews* **12**: 357–374.
- Roncaglia, L. 2004. Palynofacies analysis and organic-walled dinoflagellate cysts as indicators of palaeo-hydrographic changes: an example from Holocene sediments in Skalafjord, Faroe Islands. *Marine Micropaleontology* **50**: 21–42.
- Saenger, C., Came, R.E., Oppo, D.W., Keigwin, L.D., and Cohen, A.L. 2011. Regional climate variability in the western subtropical North Atlantic during the past two millennia. *Paleoceanography* **26**: 10.1029/2010PA002038.
- Sangiorgi, F., Capotondi, L., and Brinkhuis, H. 2002. A centennial scale organic-walled dinoflagellate cyst record of the last deglaciation in the South Adriatic Sea (Central Mediterranean). *Palaeogeography, Palaeoclimatology, Palaeoecology* **186**: 199–216.
- Sejrup, H.P., Hafliðason, H., and Andrews, J.T. 2011. A Holocene North Atlantic SST record and regional climate variability. *Quaternary Science Reviews* **30**: 3181–3195.
- Sejrup, H.P., Lehman, S.J., Hafliðason, H., Noone, D., Muscheler, R., Berstad, I.M., and Andrews, J.T. 2010. Response of Norwegian Sea temperature to solar forcing since 1000 A.D. *Journal of Geophysical Research* **115**: 10.1029/2010JC006264.
- Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., and Waple, A. 2001. Solar forcing of regional climate during the Maunder Minimum. *Science* **294**: 2149–2152.
- Watanabe, T., Winter, A., and Oba, T. 2001. Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and $^{18}\text{O}/^{16}\text{O}$ ratios in corals. *Marine Geology* **173**: 21–35.
- Winter, A., Ishioroshi, H., Watanabe, T., Oba, T., and Christy, J. 2000. Caribbean sea surface temperatures: two-to-three degrees cooler than present during the Little Ice Age. *Geophysical Research Letters* **27**: 3365–3368.
- Wu, W., Tan, W., Zhou, L., Yang, H., and Xu, Y. 2012. Sea surface temperature variability in the southern Okinawa Trough during last 2700 years. *Geophysical Research Letters* **39**: 10.1029/2012GL052749.

4.2.4.8.3 Past Century

Dippner and Ottersen (2001) produced a twentieth century (1900–1995) history of mean sea water temperature from the surface to a depth of 200 meters for the Kola Section of the Barents Sea, which stretches from 70°30'N to 72°30'N along the 33°30' E meridian. The record they developed indicates the mean temperature of the upper 200 meters of water rose by approximately 1°C from 1900 to 1940, after which it declined until about 1980 and then rose to the end of the record. The latter increase was not great enough to bring water temperatures back to the highs they experienced in the 1940s and early 1950s, and a linear regression from 1940 onward (or even 1930 onward) would produce a negative slope indicative of an overall cooling trend over the final 55 (or 65) years of the record.

Bratcher and Giese (2002) note the general trend of global surface air temperature was one of warming, but they caution there was “considerable variation in the upward trend,” and “how much of this variability is attributable to natural variations and how much is due to anthropogenic contributions to atmospheric greenhouse gases has not yet been resolved.” They add, “the possibility exists that some portion of the recent increase in global surface air temperature is part of a naturally oscillating system.” Hence, they explore “the recent record of Southern Hemisphere subsurface [ocean water] temperature anomalies and whether they may be an indicator of future global surface air temperature trends.”

The two researchers found “low frequency changes of tropical Pacific temperature lead global surface air temperature changes by about four years,”

and “anomalies of tropical Pacific surface temperature are in turn preceded by subsurface temperature anomalies in the southern tropical Pacific by approximately seven years.” In addition, they document a distinct cooling of the southern tropical Pacific over the prior eight years, leading them to conclude “the warming trend in global surface air temperature observed since the late 1970s may soon weaken.” They proved correct, as the previous upward trend in the globe’s mean surface air temperature—from the time of their writing—not only weakened but reversed course and began to trend downward.

Chavez *et al.* (2003) analyzed “physical and biological fluctuations with periods of about 50 years that are particularly prominent in the Pacific Ocean,” including air and ocean temperatures, atmospheric CO₂ concentration, landings of anchovies and sardines, and the productivity of coastal and open ocean ecosystems. They found “sardine and anchovy fluctuations are associated with large-scale changes in ocean temperatures: for 25 years, the Pacific is warmer than average (the warm, sardine regime) and then switches to cooler than average for the next 25 years (the cool, anchovy regime).” They also found “instrumental data provide evidence for two full cycles: cool phases from about 1900 to 1925 and 1950 to 1975 and warm phases from about 1925 to 1950 and 1975 to the mid-1990s.” These warm and cool regimes, which they respectively called El Viejo (“the old man”) and La Vieja (“the old woman”), were manifest in myriad similar-scale biological fluctuations that may be even better indicators of climate change than climate data themselves, in the researchers’ estimation.

The findings of this unique study have many ramifications, especially the challenge they present for the detection of CO₂-induced global warming. Chavez *et al.* note, for example, data used in climate change projections are “strongly influenced by multidecadal variability of the sort described here, creating an interpretive problem.” They conclude “these large-scale, naturally occurring variations must be taken into account when considering human-induced climate change.” The warming of the late 1970s to late 1990s, which returned much of the world to the level of warmth experienced during the 1930s and 1940s, has ended and reversed course. Chavez *et al.* cite evidence that indicates a change from El Viejo to La Vieja conditions was already in progress at the time of their writing.

Breaker (2005) performed statistical analyses on a

daily sea-surface temperature (SST) record from the Hopkins Marine Station in Pacific Grove, California (USA), located at the southern end of Monterey Bay, for the period 1920–2001, to identify and estimate the relative importance of atmospheric and oceanic processes that contribute to the variability in the SST record on seasonal to interdecadal time scales. Based on monthly averages, Breaker found approximately 44 percent of the variability in the Pacific Grove data came from the annual cycle, 18 percent from El Niño warming episodes, 6 percent from the Pacific Decadal Oscillation (PDO), 4 percent from the long-term trend, and 3 percent from the semiannual cycle. Linear analysis of the 82-year record revealed a statistically significant SST increase of 0.01°C per year, and this trend is similar to the findings of other researchers who have attributed the trend to CO₂-induced global warming. Further analyses by Breaker suggest this attribution may have been premature.

Breaker discovered two major regime shifts associated with the PDO over the course of the record, one at about 1930 and one in 1976, which could explain most of the 82-year warming. Prior to the regime shift around 1930, for example, the waters of Monterey Bay were, in Breaker’s words, “much colder than at any time since then.” And if one computes the linear SST trend subsequent to this regime shift, which Breaker did, the resulting 72-year trend is a non-statistically significant +0.0042°C. Breaker concludes, “although the long-term increase in SST at Pacific Grove appears to be consistent with global warming, the integrated anomaly suggests that temperature increases in Monterey Bay have occurred rather abruptly and thus it becomes more difficult to invoke the global warming scenario.”

Breaker’s study clearly demonstrates decadal-scale regime shifts can dwarf any potential “fingerprint” of CO₂-induced global warming that might be present in twentieth century SST datasets. Also, it is clear the regime shift around 1930 was not the product of anthropogenic-induced global warming, because so little of the current burden of anthropogenic greenhouse gases had been released to the atmosphere prior to that time compared to what was subsequently released.

Hobson *et al.* (2008) used SST data from the International Comprehensive Ocean-Atmosphere Data Set to calculate, in annual time steps, the mean August–September positions of the 12, 15, and 18°C isotherms in the North Atlantic Ocean from 1854 to 2005 at 2-degree longitudinal intervals. They found the three isotherms “have tended to move northwards

Observations: Temperature Records

during two distinct periods: in the 1930s–1940s and then again at the end of the 20th century”; “the chances of this occurring randomly are negligible”; the 15°C isotherm “reached a maximum latitude of 52.0°N in 1932, and a latitude of 51.7°N in 2005, a difference of approximately 33 km”; and “of the 10 most extreme years, 4 have occurred in the 1992–2005 warm era and 3 have occurred in the 1926–1939 era.”

The UK and Australian researchers conclude, “current ‘warm era conditions’ do not eclipse prior ‘warm’ conditions during the instrumental record,” indicating the period of most significant greenhouse gas buildup over the past century (1930 and onward) brought little or no net increase in SSTs throughout this large sector of the North Atlantic Ocean.

DeCastro *et al.* (2009) employed two sea surface temperature (SST) datasets to reconstruct the SST history of the Bay of Biscay for the period 1854–2007: an extended reconstructed SST history obtained from NOAA/OAR/ESRL PSD of Boulder, Colorado, USA, for the period 1854–1997; and weekly mean SST data obtained from nighttime measurements made by Advanced Very-High Resolution Radiometers onboard NOAA satellites for the period 1985–2006. They did so, they write, “to put the intensity of the present warming trend within the context of the last two centuries.”

The authors report, “two consecutive warming-cooling cycles were detected during the period 1854–2007: cooling from 1867 to 1910 (–0.14°C per decade); warming from 1910 to 1945 (0.17°C per decade); cooling from 1945 to 1974 (–0.10°C per decade); and warming from 1974 to 2007 (0.22°C per decade).” The four Spanish scientists state, “the present warming period (1974–2007) is on the same order of magnitude although slightly more intense than the one observed from 1910 to 1945.” They conclude, “this fact does not permit elucidating the possible anthropogenic influence on the present day warming, which still remains an open question.” This conclusion, they write, “is consistent with the analysis carried out by Hobson *et al.* (2008) for the North Atlantic,” who also conclude “current ‘warm era conditions’ do not eclipse prior ‘warm’ conditions during the instrumental record.” With respect to sea surface temperature, they observe, “the North Atlantic remains within the envelope of previous recorded conditions.”

Halfar *et al.* (2011) state, “mid- and high-latitude crustose coralline algae are an emerging extra-tropical marine climate archive,” as was demonstrated during

a field calibration study (Halfar *et al.*, 2008), because “they are amongst the longest-lived shallow marine organisms (Frantz *et al.*, 2005),” and “they show constant growth over their lifespan and are not subject to an ontogenetic growth trend with skeletal age.” Using “a regional network of specimens of the coralline alga *Clathromorphum compactum* spanning portions of the Labrador Current inshore branch from the Gulf of St. Lawrence to both latitudinal extremes of the eastern Newfoundland shelf,” the authors generated “a 115-year-long growth-increment-width based record of subarctic northwest Atlantic surface temperatures.”

The new temperature reconstruction reveals “the well-documented regime shift and warming in the northwestern Atlantic during the 1990s.” The eight researchers further report, “large positive changes in algal growth anomalies were also present in the 1920s and 1930s, indicating the impact of a concurrent large-scale regime shift throughout the North Atlantic was more strongly felt in the subarctic Northwestern Atlantic than previously thought.” They state this regime shift “may have even exceeded the 1990s event with respect to the magnitude of the warming,” as “has recently been suggested for the central and eastern North Atlantic,” citing Drinkwater (2006).

This study adds to a large body of evidence documenting warmer temperatures in the 1920s and 1930s than in the late 1990s/early 2000s, an observation at odds with the IPCC’s claims the warming of the past two decades is unprecedented over the past millennium or more. The air’s CO₂ concentration in the 1920s and 1930s was roughly 300–305 ppm; today’s atmospheric CO₂ concentration is about 400 ppm, some 30 percent greater than during those warmer times.

References

- Bratcher, A.J. and Giese, B.S. 2002. Tropical Pacific decadal variability and global warming. *Geophysical Research Letters* **29**: 10.1029/2002GL015191.
- Breaker, L.C. 2005. What’s happening in Monterey Bay on seasonal to interdecadal time scales? *Continental Shelf Research* **25**: 1159–1193.
- Chavez, F.P., Ryan, J., Lluch-Cota, S.E., and Niquen C., M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* **299**: 217–221.
- deCastro, M., Gomez-Gesteira, M., Alvarez, I., and Gesteira, J.L.G. 2009. Present warming within the context

of cooling-warming cycles observed since 1854 in the Bay of Biscay. *Continental Shelf Research* **29**: 1053–1059.

Dippner, J.W. and Ottersen, G. 2001. Cod and climate variability in the Barents Sea. *Climate Research* **17**: 73–82.

Drinkwater, K. 2006. The regime shift of the 1920s and 1930s in the North Atlantic. *Progress in Oceanography* **68**: 134–151.

Frantz, B.R., Foster, M.S., and Riosmena-Rodriguez, R. 2005. *Clathromorphum nereostratum* (Corallinales, Rhodophyta): the oldest alga? *Journal of Phycology* **41**: 770–773.

Halfar, J., Hetzinger, S., Adey, W., Zack, T., Gamboa, G., Kunz, B., Williams, B., and Jacob, D.E. 2011. Coralline algal growth-increment widths archive North Atlantic climate variability. *Palaeogeography, Palaeoclimatology, Palaeoecology* **302**: 71–80.

Halfar, J., Steneck, R.S., Joachimski, M., Kronz, A., and Wanamaker Jr., A.D. 2008. Coralline red algae as high-resolution climate recorders. *Geology* **36**: 463–466.

Hobson, V.J., McMahon, C.R., Richardson, A., and Hays, G.C. 2008. Ocean surface warming: The North Atlantic remains within the envelope of previous recorded conditions. *Deep-Sea Research I* **55**: 155–162.

4.2.8.4.4 Past Few Decades

What do ocean temperatures tell us about the theory of CO₂-induced global warming? This section considers what can and cannot be inferred from studies of the past few decades.

In a *Science* news story highlighting the work of Levitus *et al.* (2000), Richard Kerr's title all but announced the finding of climatology's Holy Grail: "Globe's 'Missing Warming' Found in the Ocean." Was that really the case? Before considering this question, it is instructive to note Kerr clearly acknowledges much of the warming that had long been predicted to occur as a consequence of the historical rise in the atmosphere's CO₂ concentration had indeed been missing. That is to say, his choice of words was admmissive of the fact that Earth's atmosphere had not warmed by the amount that had long been predicted.

So how much of the missing warming was supposedly found? In a detailed analysis of a vast array of oceanic temperatures spanning the globe and extending from the surface down to a depth of 3,000 meters, Levitus *et al.* detected an incredibly small 0.06°C temperature increase between the mid-1950s and mid-1990s. Because the world's oceans have a

combined mass 2,500 times greater than that of the atmosphere, this figure, as small as it seems, was truly significant. But was it correct?

Although their data extended back in time several years beyond the point at which they specified the warming to begin, Levitus *et al.* computed the linear trend in temperature between the lowest valley of their oscillating time series and its highest peak, ensuring they would obtain the largest warming possible. Over a moderately longer time period, global ocean warming would have been computed to be much less than what Levitus *et al.* reported, and the extended record would make the rate of warming smaller still. Nevertheless, NASA's James Hansen was quoted by Kerr as saying the new ocean-warming data "imply that climate sensitivity is not at the low end of the spectrum" that had typically been considered plausible.

But scientists were not interested only in the magnitude of the warming; they also wondered about cause. Climate modeler Jerry Mahlman, for example, stated, according to Kerr, that the study of Levitus *et al.* "adds credibility to the belief that most of the warming in the 20th century is anthropogenic." Yet Levitus *et al.* had clearly stated in their *Science* paper, "we cannot partition the observed warming to an anthropogenic component or a component associated with natural variability," which brings us to the subject of climate sensitivity. To calculate such a parameter one must have values for both a climate forcing and a climate response. If one cannot identify the source of the forcing, much less its magnitude, it is clearly impossible to calculate a sensitivity.

Levitus *et al.* (2001) and Barnett *et al.* (2001) added to the documentation of the modest warming of the planet's deep oceans. With respect to this accomplishment, Lindzen (2002) wrote, "the fact that models forced by increasing CO₂ and tuned by nominal inclusion of aerosol effects to simulate the global mean temperature record for the past century roughly matched the observed deep ocean record was taken as evidence of the correctness of the models and of the anthropogenic origin of the deep ocean warming." However, he took strong exception to this conclusion.

Assuming the deep-ocean temperature measurements and their analysis were correct, Lindzen used a coupled climate model (an energy balance model with a mixed layer diffusive ocean) "to examine whether deep ocean temperature behavior from 1950 to 2000 actually distinguishes between models of radically different sensitivity to doubled

Observations: Temperature Records

CO₂.” This revealed the warming of the deep oceans, in Lindzen’s words, “is largely independent of model sensitivity,” which led him to conclude “the behavior of deep ocean temperatures is not a test of model sensitivity, but rather a consequence of having the correct global mean surface temperature time history.” He notes, “we are dealing with observed surface warming that has been going on for over a century” and “the oceanic temperature change over the period 1950–2000 reflects earlier temperature changes at the surface.”

Further to this point, it should be noted according to the data of Esper *et al.* (2002), the Earth began to warm in the early 1800s, and the warming of the twentieth century, according to Briffa and Osborn (2002), was “a continuation of a trend that began at the start of the 19th century.” Earth had completed the bulk of its post-Little Ice Age temperature rebound well before much of the Industrial Revolution’s CO₂ emissions entered the atmosphere; i.e., by about 1930. As a result, the modest rise in deep-water temperatures over the past half-century or so tells us nothing about the sensitivity of Earth’s climate to atmospheric CO₂ enrichment, nor does it link the warming to anthropogenic CO₂ emissions.

He *et al.* (2002) used stable oxygen isotope data acquired from a core of *Porites lutea* coral on the east of Hainan Island in the South China Sea to develop a 56-year (1943–1998) history of sea surface temperature in that region. They report the sea surface temperature in the 1940s “was warmer than that in the 1980s–1990s,” by as much as 1.5°C.

Motivated by reports of “extraordinary change in the Arctic Ocean observed in recent decades,” Polyakov *et al.* (2003) began their study by referencing the work of Carmack *et al.* (1995) and Woodgate *et al.* (2001), who had reported evidence of positive Atlantic Layer Core Temperature (ALCT) anomalies of up to 1°C in the 150- to 800-meter depth interval. Polyakov *et al.* note, however, an evaluation of the significance of these anomalies “requires an understanding of the underlying long-term variability” of the pertinent measurements.

The data employed by Polyakov *et al.* included temperature and salinity measurements from Russian winter surveys of the central Arctic Ocean carried out over the period 1973–1979, derived from 1034 oceanographic stations and constituting “the most complete set of arctic observations.” In addition, they utilized 40 years of summer and winter observations from the Laptev Sea. Based on these comprehensive measurements, they determined new statistical

estimates of long-term variability in both ALCT and sea-surface salinity (SSS). This work demonstrates the standard dataset that had been used to suggest the existence of the apparent 1°C temperature anomalies of the 1990s “considerably underestimates variability,” as the observed ALCT anomalies in the late 1970s were fully as great as those of the 1990s.

Polyakov *et al.* state their new statistical analyses placed “strong constraints on our ability to define long-term means,” as well as the magnitudes of ALCT and SSS anomalies computed using synoptic measurements from the 1990s referenced to means from earlier climatologies. Consequently, what some had described as “the extraordinary change in the Arctic Ocean observed in recent decades” turned out to be not extraordinary at all; it was merely a reappearance of conditions that had prevailed a few years earlier.

Freeland *et al.* (2003) analyzed water temperature and salinity measurements made at a number of depths over a period of several years along two lines emanating from central Oregon and Vancouver Island westward into the Pacific Ocean. The data indicate subsurface waters in an approximate 100-meter-thick layer located between 30 and 150 meters depth off central Oregon were, in the words of the researchers, “unexpectedly cool in July 2002.” Mid-depth temperatures over the outer continental shelf and upper slope were more than 0.5°C colder than the historical summer average calculated by Smith *et al.* (2001) for the period 1961–2000, which Freeland *et al.* state, “might be cooler than a longer-term mean because the 1961–71 decade coincided with a cool phase of the Pacific Decadal Oscillation (Mantua *et al.*, 1997).” At the most offshore station, they report “the upper halocline [was] >1°C colder than normal and about 0.5°C colder than any prior observation.” In addition to being substantially cooler, the anomalous water was also much fresher, and the combined effects of these two phenomena made the water less “spicy,” as Freeland *et al.* describe it—so much so that they refer to the intensity of the spiciness anomaly as “remarkable.”

Along the line that runs from the mouth of Juan de Fuca Strait to Station Papa at 50°N, 145°W in the Gulf of Alaska, which was sampled regularly between 1959 and 1981 and irregularly thereafter, similarly low spiciness was observed, which in the researchers’ opinion is the same feature as detected off the coast of central Oregon. They report “conditions in June 2002 [were] well outside the bounds of all previous experience,” and “in summer 2001 the spiciness of

this layer was already at the lower bound of previous experience.”

Freeland *et al.* conclude their data implies “the waters off Vancouver Island and Oregon in July 2002 were displaced about 500 km south of their normal summer position.” Was this observation an indication the Pacific Ocean was beginning to experience a shift from what Chavez *et al.* (2003) called a “warm, sardine regime” to a “cool, anchovy regime”? It is tempting to suggest it was. Freeland *et al.* cautioned against jumping to such a conclusion, saying there were no obvious signals of such a regime shift in several standard climate indices and that without evidence of a large-scale climate perturbation, the spiciness anomaly might have been simply anomalous. Consequently, although the pattern of Pacific Ocean regime shifts documented by Chavez *et al.* suggest a change from warmer to cooler conditions might have been imminent, there was not at that time sufficient climatic evidence to conclude such a shift was occurring.

In reference to the 1976–1977 regime shift in the Pacific, Chavez *et al.* note, “it took well over a decade to determine that a regime shift had occurred in the mid-1970s” and hence, “a regime or climate shift may even be best determined by monitoring marine organisms rather than climate,” as suggested by Hare and Mantua (2000). Chavez *et al.* cite several studies that appeared to provide such evidence, including “a dramatic increase in ocean chlorophyll off California,” which would seem a logical response to what Freeland *et al.* described as “an invasion of nutrient-rich Subarctic waters.” Other pertinent evidence cited by Chavez *et al.* includes “dramatic increases in baitfish (including northern anchovy) and salmon abundance off Oregon and Washington” and “increases in zooplankton abundance and changes in community structure from California to Oregon and British Columbia, with dramatic increases in northern or cooler species.”

McPhaden and Zhang (2004) report between the mid-1970s and mid-1990s sea surface temperatures in the eastern and central equatorial Pacific Ocean rose by about 0.7°C in response to a slowdown of the shallow meridional overturning circulation, and some scientists had suggested these phenomena were the result of greenhouse gas forcing. They also note the existence of evidence for a late 1990s “regime shift” in the North Pacific (Chavez *et al.*, 2003; Peterson and Schwing, 2003) that could temper or even refute the other interpretation of the data.

Since year-to-year fluctuations associated with El

Niño and La Niña conditions can greatly influence Earth’s climate system, the two researchers compared mean conditions in the eastern and central equatorial Pacific Ocean for the six-year period July 1992–June 1998 with the more recent five-year period July 1998–June 2003, both of which intervals spanned at least one complete ENSO warm and cold phase cycle. In addition to sea surface temperatures, their investigation utilized hydrographic and wind data spanning the period 1992–2003 to calculate geostrophic meridional volume transports in the upper pycnocline of the tropical Pacific.

These data and analyses indicated “the shallow meridional overturning circulation in the tropical Pacific Ocean has rebounded since 1998, after 25 years of significantly weaker flow.” McPhaden and Zhang determined it had “recently rebounded to levels almost as high as in the 1970s.” Likewise, the area-averaged sea surface temperature in the eastern and central equatorial Pacific Ocean concurrently dropped approximately 0.6°C to almost equal the low of the mid-1970s and match the low of the previous regime in the mid-1950s.

McPhaden and Zhang conclude the “precise magnitude of anthropogenic influences [on tropical Pacific sea surface temperatures] will be difficult to extract with confidence from the instrumental record given the rapidity with which observed warming trends can be reversed by natural variations.”

Lyman *et al.* (2006) note, “with over 1000 times the heat capacity of the atmosphere, the World Ocean is the largest repository for changes in global heat content,” and “monitoring ocean heat content is therefore fundamental to detecting and understanding changes in the Earth’s heat balance.” Consequently, “using a broad array of in situ temperature data from expendable bathythermographs, ship board conductivity-temperature-depth sensors, moored buoy thermistor records, and autonomous profiling conductivity-temperature-depth floats,” they estimated the global integral of ocean heat content anomaly of the upper 750 meters from the start of 1993 through the end of 2005.

This undertaking revealed that from 1993 to 2003 the heat content of the upper 750 meters of the world ocean increased by $8.1 (\pm 1.4) \times 10^{22}$ J, but “this increase was followed by a decrease of $3.2 (\pm 1.1) \times 10^{22}$ J between 2003 and 2005.” This decrease, they write, “represents a substantial loss of heat over a 2-year period, amounting to about one fifth of the long-term upper-ocean heat gain between 1955 and 2003 reported by Levitus *et al.* (2005).” They also found

Observations: Temperature Records

“the maximum cooling occurs at about 400 m,” and “the cooling signal is still strong at 750 m and appears to extend deeper.” They report preliminary estimates “show that additional cooling occurred between depths of 750 and 1400 m.” As for the source of the cooling, they say it “could be the result of a net loss of heat from the Earth to space.”

Lyman *et al.* note the physical causes of the type of variability they discovered “are not yet well understood,” and “this variability is not adequately simulated in the current generation of coupled climate models used to study the impact of anthropogenic influences on climate,” which “may complicate detection and attribution of human-induced climate influences.” This statement suggests there has not yet been an adequate demonstration of human-induced influences on world ocean temperatures. It also would appear there currently is little hope of finding such a connection in subsets of world ocean data any time soon, for “the relatively small magnitude of the globally averaged signal is dwarfed by much larger regional variations in ocean heat content anomaly.” Whereas “the recent decrease in heat content amounts to an average cooling rate of $-1.0 \pm 0.3 \text{ Wm}^{-2}$ (of the Earth’s total surface area) from 2003 to 2005,” regional variations “sometimes exceed the equivalent of a local air-sea heat flux anomaly of 50 Wm^{-2} applied continuously over 2 years.”

Noting the global-scale study of the world’s oceans conducted by Levitus *et al.* (2005) suggested a significant increase in the heat content of the upper 3-km layer between 1957 and 1997, Gouretski and Koltermann (2007) contend Levitus *et al.* did not take into account “possible temperature biases associated with differing instrumentation.” The large database employed by Levitus *et al.* was derived from five types of instruments—mechanical and expandable bathythermographs (MBTs and XBTs), hydrographic bottles (Nansen and Rosette), conductivity-temperature-depth (CTD) instruments, and profiling floats—and they analyzed temperature offsets among them and applied their findings to temporal trends in the degree of each type of instrument’s usage over the period in question.

Gouretski and Koltermann note XBT data comprised the largest proportion of the total database, and “with XBT temperatures being positively biased by $0.2\text{--}0.4^\circ\text{C}$ on average,” this bias resulted in “a significant World Ocean warming artifact when time periods before and after introduction of XBTs [were] compared.” When Gouretski and Koltermann used the bias-correction techniques they developed, the ocean

heat content increase since the 1950s was reduced by a factor of 0.62. They write, “such corrections if applied would correspondingly reduce the estimate of the ocean warming in Levitus *et al.* (2005) calculations.” Gouretski and Koltermann’s work indicates the warming of the global ocean over the last half of the twentieth century as calculated by Levitus *et al.* (2005) was seriously overestimated.

Harrison and Carson (2007) sorted individual temperature observations in the World Ocean Database 2001 into $1^\circ \times 1^\circ$ and $2^\circ \times 2^\circ$ bins, after which, working only with bins having at least five observations per decade for four of the five decades since 1950, they calculated 51-year temperature trends for depths of 100, 300, and 500 meters, as well as sequential 20-year trends—i.e., 1950–1970, 1955–1975, 1960–1980, and 1980–2000—for the same depths. Based on the results, which were statistically significant at the 90% confidence level, they determined the upper ocean “is replete with variability in space and time, and multi-decadal variability is quite energetic almost everywhere.” They found 95 percent of the $2^\circ \times 2^\circ$ regions they studied “had both warming and cooling trends over sequential 20-year periods,” and “the 51-year trends are determined in a number of regions by large trends over 20- to 25-year sub-periods.” They conclude, “trends based on records of one or two decades in length are unlikely to represent accurately longer-term trends,” and, therefore, “it is unwise to attempt to infer long-term trends based on data from only one or two decades.” In addition, they note, “the magnitude of the 20-year trend variability is great enough to call into question how well even the statistically significant 51-year trends ... represent longer-term trends.”

Carson and Harrison (2008) derived and analyzed ocean temperature trends over the period 1955–2003 at depths ranging from 50 to 1,000 meters to “test the sensitivity of trends to various data processing methods.” They used the *World Ocean Database 2005* (Boyer *et al.*, 2006), employed the analytical approach of Harrison and Carson (2007), and compared their results with those of Levitus *et al.* (2005). They find, “most of the ocean does not have significant 50-year trends at the 90% confidence level (CL).” They state, “only 30% of the ocean at 50 meters has 90% CL trends, and the percentage decreases significantly with increasing depth.” In comparison with prior calculated trends, they also report the results “can differ substantially, even in the areas with statistically significant trends,” noting,

“trends based on the more interpolated analyses,” such as those of Levitus *et al.* (2005), “show more warming.” Thus the two researchers conclude, “ocean heat content integrals and integral trends may be substantially more uncertain than has yet been acknowledged.”

In concluding this summary of the global ocean’s thermal behavior over the past few decades, we discuss two papers that deal more with processes than with history. The first of these papers is that of Kleypas *et al.* (2008), who looked for evidence of an ocean thermostat by analyzing patterns of sea surface temperature (SST) increases in the tropics over the past five decades. They focused their attention on the western Pacific warm pool (WPWP), because, they write, “this is a region where maximum SSTs are thought to be limited by negative feedbacks,” as described in the writings of Reginald Newell (1979), whom they cite and who in collaboration with Thomas Dopplack demonstrated, nearly three decades ago, that the degree of CO₂-induced global warming predicted by the climate models of that day was far greater (and is greater still today) than what is allowed by the real world (Newell and Dopplack, 1979), as further described in the historical narrative of Idso (1982).

Kleypas *et al.* say their analysis indicates “the warmest parts of the WPWP have warmed less than elsewhere in the tropical oceans,” which “supports the existence of thermostat mechanisms that act to depress warming beyond certain temperature thresholds.” In addition, they report “coral reefs within or near the WPWP have had fewer reported bleaching events relative to reefs in other regions,” which is also indicative of the existence of an upper-limiting temperature above which SSTs typically do not rise, presumably because the oceanic thermostat kicks in when they approach 30°C in the region the three researchers describe as “the center of coral reef biodiversity.”

These findings support the thesis put forward years ago by both Newell and Dopplack (1979) and Idso (1980, 1982, 1989): that rather than Earth possessing some thermal “tipping point” above which global warming dramatically accelerates, the planet’s climatic system does just the opposite and greatly attenuates warming above a certain level.

Shaviv (2008) begins by noting “climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales,” citing numerous references, many more of which can be found in Chapter 3 of this volume.

Nevertheless, it is difficult for some to accept the logical derivative of this fact—that solar variations are driving major climate changes—their prime objection being that measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes.

One potential way to resolve this dilemma would be to discover some amplification mechanism, but most attempts have been fraught with difficulty and met with much criticism. Shaviv, however, makes a good case for at least the existence of such an amplifier, and he points us in the direction of a sensible candidate to fill this role.

Shaviv used “the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle” via “the study of three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations,” each of which can be used, in his words, “to consistently derive the same oceanic heat flux.”

Shaviv demonstrates “there are large variations in the oceanic heat content together with the 11-year solar cycle.” In addition, he reports the three independent datasets “consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance,” thus “implying,” as he describes it, “the necessary existence of an amplification mechanism, although without pointing to which one.”

Shaviv nonetheless acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis suggested by Ney (1959), discussed by Dickenson (1975), and championed by Svensmark (1998). Based on “correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions,” this concept, according to Shaviv, “predicts the correct radiation imbalance observed in the cloud cover variations” needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle.

Shaviv thus concludes the solar-wind modulated CRF hypothesis is “a favorable candidate” for primary instigator of the many climatic phenomena described in this volume.

Even with all the data that have been acquired

Observations: Temperature Records

over the past half-century, it remains difficult to state with much confidence exactly what the world's oceans are doing in terms of the storage and loss of heat. To state precisely *why* they are doing whatever it is they are doing is even more difficult.

References

- Barnett, T.P., Pierce, D.W., and Schnur, R. 2001. Detection of anthropogenic climate change in the world's oceans. *Science* **292**: 270–273.
- Boyer, T.P. and coauthors. 2006. *World Ocean Database 2005*. NOAA Atlas NESDIS 60.
- Briffa, K.R. and Osborn, T.J. 2002. Blowing hot and cold. *Science* **295**: 2227–2228.
- Carmack, E.C., Macdonald, R.W., Perkin, R.G., McLaughlin, F.A., and Pearson, R.J. 1995. Evidence for warming of Atlantic water in the southern Canadian Basin of the Arctic Ocean: Results from the Larsen-93 expedition. *Geophysical Research Letters* **22**: 1061–1064.
- Carson, M. and Harrison, D.E. 2008. Is the upper ocean warming? comparisons of 50-year trends from different analyses. *Journal of Climate* **21**: 2259–2268.
- Chavez, F.P., Ryan, J., Lluch-Cota, S.E., and Niquen C., M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* **299**: 217–221.
- Dickinson, R.E. 1975. Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* **56**: 1240–1248.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Freeland, H.J., Gatién, G., Huyer, A., and Smith, R.L. 2003. Cold halocline in the northern California Current: An invasion of subarctic water. *Geophysical Research Letters* **30**: 10.1029/2002GL016663.
- Gouretski, V. and Koltermann, K.P. 2007. How much is the ocean really warming? *Geophysical Research Letters* **34**: 10.1029/2006GL027834.
- Hare, S.R. and Mantua, N.J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* **47**: 103–145.
- Harrison, D.E. and Carson, M. 2007. Is the world ocean warming? Upper-ocean temperature trends: 1950–2000. *Journal of Physical Oceanography* **37**: 174–187.
- He, X., Liu, D., Peng, Z., and Liu, W. 2002. Monthly sea surface temperature records reconstructed by $\delta^{18}\text{O}$ of reef-building coral in the east of Hainan Island, South China Sea. *Science in China Series B* **45**: 130–136.
- Idso, S.B. 1980. The climatological significance of a doubling of Earth's atmospheric carbon dioxide concentration. *Science* **207**: 1462–1463.
- Idso, S.B. 1982. *Carbon Dioxide: Friend or Foe?* IBR Press, Tempe, Arizona, USA.
- Idso, S.B. 1989. *Carbon Dioxide and Global Change: Earth in Transition*. IBR Press, Tempe, Arizona, USA.
- Kerr, R.A. 2000. Globe's "missing warming" found in the ocean. *Science* **287**: 2126–2127.
- Kleypas, J.A., Danabasoglu, G., and Lough, J.M. 2008. Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. *Geophysical Research Letters* **35**: 10.1029/2007GL032257.
- Levitus, S.J., Antonov, I., and Boyer, T.P. 2005. Warming of the world ocean, 1955–2003. *Geophysical Research Letters* **32**: 10.1029/2004GL021592.
- Levitus, S., Antonov, J.I., Boyer, T.P., and Stephens, C. 2000. Warming of the world ocean. *Science* **287**: 2225–2229.
- Levitus, S., Antonov, J.I., Wang, J., Delworth, T.L., Dixon, K.W., and Broccoli, A.J. 2001. Anthropogenic warming of Earth's climate system. *Science* **292**: 267–270.
- Lindzen, R.S. 2002. Do deep ocean temperature records verify models? *Geophysical Research Letters* **29**: 10.1029/2001GL014360.
- Lyman, J.M., Willis, J.K., and Johnson, G.C. 2006. Recent cooling of the upper ocean. *Geophysical Research Letters* **33**: 10.1029/2006GL027033.
- Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.
- McPhaden, M.J. and Zhang, D. 2004. Pacific Ocean circulation rebounds. *Geophysical Research Letters* **31**: 10.1029/2004GL020727.
- Newell, R.E. 1979. Climate and the ocean. *American Scientist* **67**: 405–416.
- Newell, R.E. and Doplick, T.G. 1979. Questions concerning the possible influence of anthropogenic CO_2 on atmospheric temperature. *Journal of Applied Meteorology* **18**: 822–825.
- Ney, E.P. 1959. Cosmic radiation and weather. *Nature* **183**: 451.
- Peterson, W.T. and Schwing, F.B. 2003. A new climate

regime in the northeast Pacific Ocean. *Geophysical Research Letters* **30**: 10.1029/2003GL017528.

Polyakov, I., Walsh, D., Dmitrenko, I., Colony, R.L., and Timokhov, L.A. 2003. Arctic Ocean variability derived from historical observations. *Geophysical Research Letters* **30**: 10.1029/2002GL016441.

Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* **113**: 10.1029/2007JA012989.

Smith, R.L., Huyer, A., and Fleischbein, J. 2001. The coastal ocean off Oregon from 1961 to 2000: is there evidence of climate change or only of Los Niños? *Progress in Oceanography* **49**: 63–93.

Svensmark, H. 1998. Influence of cosmic rays on Earth's climate. *Physical Review Letters* **81**: 5027–5030.

Woodgate, R.A., Aagaard, K., Muench, R.D., Gunn, J., Bjork, G., Rudels, B., Roach, A.T., and Schauer, U. 2001. The Arctic Ocean boundary current along the Eurasian slope and the adjacent Lomonosov Ridge: water mass properties, transports and transformations from moored instruments. *Deep Sea Research, Part I* **48**: 1757–1792.

4.2.4.9 South America

As indicated in the introduction of Section 4.2.4, data presented in numerous peer-reviewed studies reveal modern temperatures are not unnatural. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration. Conditions as warm as or warmer than the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO₂ concentration remained at values approximately 30 percent lower than today's.

The following subsections highlight studies addressing this topic in South America. Much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; the Current Warm Period is simply the latest manifestation. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

4.2.4.9.1 Argentina

Cioccale (1999) assembled what was known at the time about the climatic history of the central region of Argentina over the past 1,400 years, highlighting a climatic “improvement” that began 400 years before the start of the last millennium, which ultimately came to be characterized by “a marked increase of environmental suitability, under a relatively homogeneous climate.” As a result of this climatic amelioration that marked the transition of the region from the Dark Ages Cold Period to the Medieval Warm Period, Cioccale reports “the population located in the lower valleys ascended to higher areas in the Andes,” where they remained until around AD 1320, when the transition to the stressful and extreme climate of the Little Ice Age began.

At the southern tip of the country, in Tierra del Fuego, Mauquoy *et al.* (2004) inferred similar changes in temperature and/or precipitation from plant macrofossils, pollen, fungal spores, testate amebae, and humification associated with peat monoliths collected from the Valle de Andorra. These new chronologies were compared with other chronologies from both the Southern and Northern Hemispheres, and the analysis showed evidence for a period of warming-induced drier conditions in AD 960–1020, which, they write, “seems to correspond to the Medieval Warm Period (MWP, as derived in the Northern Hemisphere).” They also note, “this interval compares well to the date range of AD 950–1045 based on Northern Hemisphere extratropical tree-ring data (Esper *et al.*, 2002).” They conclude this correspondence “shows that the MWP was possibly synchronous in both hemispheres, as suggested by Villalba (1994).”

Haberzettl *et al.* (2005) worked with five sediment cores extracted from Laguna Potrok Aike (51°58'S, 70°23'W), one of the few permanently water-filled lakes in the dry-lands of southern Patagonia. They analyzed a host of proxy climate indicators, finding “the sediment record of Laguna Potrok Aike reveals an unprecedented sensitive continuous high resolution lake level, vegetation and climate record for southern Patagonia since AD 400.” This history indicates the climate of the region fluctuated rapidly from the beginning of the record up to the start of the Medieval Climatic Anomaly (MCA), which Stine (1998) proposed as having begun at about AD 870. This earlier time interval corresponds with the Dark Ages Cold Period of Europe, and it was followed by the MCA, or what

Observations: Temperature Records

Europeans call the Medieval Warm Period. The latter was most strongly expressed in the Laguna Potrok Aike data from AD 1240 to 1410, during which period maxima of total inorganic carbon (TIC), total organic carbon (TOC), total nitrogen (TN), carbon/nitrogen ratio (C/N) and $\delta^{13}\text{C}_{\text{org}}$ indicate, in the words of the ten researchers, “low lake levels and warm and dry climate.”

Thereafter, the scientists continue, “the MCA ends during the 15th century” and was “followed by the so called ‘Little Ice Age.’” Finally, they write, “in the course of the 20th century, Laguna Potrok Aike reacted like many other Patagonian lakes with a lake level lowering after 1940, culminating in 1990, and followed by a subsequent rise and recession.”

As to whether it was warmer during the MCA than during the twentieth century, Haberzettl *et al.* state, “there is evidence for lower lake levels during the MCA than today in every proxy,” and “the existence of lower lake levels in former times was demonstrated by seismic studies which revealed hitherto undated fossil lake level terraces ca. 30 m below the present lake level (Zolitschka *et al.*, 2004).” In addition, “TOC and TN as proxies reflecting productivity also show higher values during the MCA than today,” even though “present TOC and TN values are elevated due to anthropogenic eutrophication.” They conclude, “this altogether implies that it might have been warmer during [AD 1240 to 1410] than today.”

References

- Cioccale, M.A. 1999. Climatic fluctuations in the Central Region of Argentina in the last 1000 years. *Quaternary International* **62**: 35–47.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Haberzettl, T., Fey, M., Lucke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schabitz, F., Schleser, G.H., Wille, M., and Zolitschka, B. 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). *Journal of Paleolimnology* **33**: 283–302.
- Mauquoy, D., Blaauw, M., van, Geel, B., Borromei, A., Quattrocchio, M., Chambers, F.M., and Possnert, G. 2004. Late Holocene climatic changes in Tierra del Fuego based on multiproxy analyses of peat deposits. *Quaternary Research* **61**: 148–158.
- Stine, S. 1998. Medieval Climatic Anomaly in the Americas. In: Issar, A.S. and Brown, N. (Eds.) *Water, Environment and Society in Times of Climatic Change*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 43–67.
- Villalba, R. 1994. Tree-ring and glacial evidence for the Medieval Warm Epoch and the ‘Little Ice Age’ in southern South America. *Climatic Change* **26**: 183–197.
- Zolitschka, B., Schabitz, F., Lucke, A., Wille, M., Mayr, C., Ohlendorf, C., Anselmetti, F., Ariztegui, D., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Maidana, N., Oliva, G., Paez, M., and Schleser, G.H. 2004. Climate changes in Southern Patagonia (Santa Cruz, Argentina) inferred from lake sediments—the multi-proxy approach of SALSA. *PAGES News* **12**(2): 9–11.

4.2.4.9.2 Brazil

Vuille *et al.* (2012) reviewed the history of the South American summer monsoon (SASM) over the past two millennia, using information obtained from high-resolution stable isotopes derived from speleothems, ice cores, and lake sediments acquired from the monsoon belt of the tropical Andes and Southeast Brazil. This work reveals “a very coherent behavior over the past two millennia with significant decadal to multidecadal variability superimposed on large excursions during three key periods: the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA) and the current warm period (CWP),” which they interpret as “times when the SASM’s mean state was significantly weakened (MCA and CWP) and strengthened (LIA), respectively.”

The nine researchers hypothesize, “these centennial-scale climate anomalies were at least partially driven by temperature changes in the Northern Hemisphere and in particular over the North Atlantic, leading to a latitudinal displacement of the Intertropical Convergence Zone and a change in monsoon intensity (amount of rainfall upstream over the Amazon Basin).” As they note the intensity of the SASM “today appears on par with conditions during the MCA,” it can be concluded the peak temperatures of the MCA and the CWP over the North Atlantic Ocean are likely on par as well, suggesting there is nothing unusual about today’s current level of warmth over the North Atlantic and today’s global level of warmth need not have been caused by the concurrent 40 percent greater atmospheric CO₂ concentration.

Reference

Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H., and Novello, V.F. 2012. A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past* 8: 1309–1321.

4.2.4.9.3 Chile

Lamy *et al.* (2001) used the iron content from an ocean sediment core taken from the Chilean continental slope (41°S, 74.45°W) as a proxy for historic rainfall in this region during the Holocene. Results indicate several centennial and millennial-scale phases of rainfall throughout this period, including an era of decreased rainfall “coinciding with the Medieval Warm Period,” which was followed by an era of increased rainfall during the Little Ice Age (see Figure 4.2.4.9.3.1). They conclude their data “provide further indications that both the LIA and MWP were global climate events.”

Jenny *et al.* (2002) studied geochemical, sedimentological, and diatom-assemblage data derived from sediment cores extracted from one of the largest natural lakes (Laguna Aculeo) in the central part of Chile. From 200 BC, when the record began, until AD 200, conditions there were primarily

dry, during the latter stages of the Roman Warm Period. Subsequently, from AD 200–700, with a slight respite in the central hundred years of that period, there was a high frequency of flood events, during the Dark Ages Cold Period. Then came a several-hundred-year period of less flooding that was coeval with the Medieval Warm Period. This more benign period was followed by another period of frequent flooding from 1300–1700 coincident with the Little Ice Age, after which flooding picked up again after 1850.

Nester *et al.* (2007) studied fluvial terraces in the Pampa del Tamarugal (PdT) basin of the Atacama Desert of northern Chile, which contains widespread fossil wood, *in situ* roots, and well-preserved leaf litter deposits indicative of perennial surface flow in now-dry channels where streams once cut canyons in the desert’s currently hyper-arid core. In this challenging environment, and based on radiocarbon dating, the five researchers determined the approximate dates of the most important recharge events of these channels of the last 18,000 years, demonstrating “there was enhanced stream discharge into the PdT during the time intervals of 17,750–13,750, 11,750, and 1,100–700 cal yr BP,” while noting “groundwater must have been near the surface (<10 m) for *Prosopis* stands to have lived [there] between 1,100–700 cal yr BP.” The latter Chilean “Medieval Climatic Anomaly (MCA),” as they describe it, “is of opposite hydrological impact (wet) to that of coastal Peru (dry), where lithic concentrations in a marine core document diminished strength of El Niño events during the MCA (Rein *et al.*, 2004).”

This wettest interval of the past 11,000-plus years in the hyper-arid core of the Atacama Desert (~AD 900–1300) coincides nicely with the central portion of the mean timeframe of the MWP as experienced around the globe. This unique set of regional circumstances—wet in the Atacama Desert of Chile and dry along coastal Peru—is a strong indication of the dramatic but varied effects of the global Medieval Warm Period in this particular part of the world.

Rebolledo *et al.* (2008) analyzed changes in marine productivity and contemporaneous terrestrial input in a study of sediment cores retrieved from the Jacaf Channel (44°S, 72°W) of Chilean Northern Patagonia that contained data pertaining to the past 1,800 years, using biogenic opal, siliceous

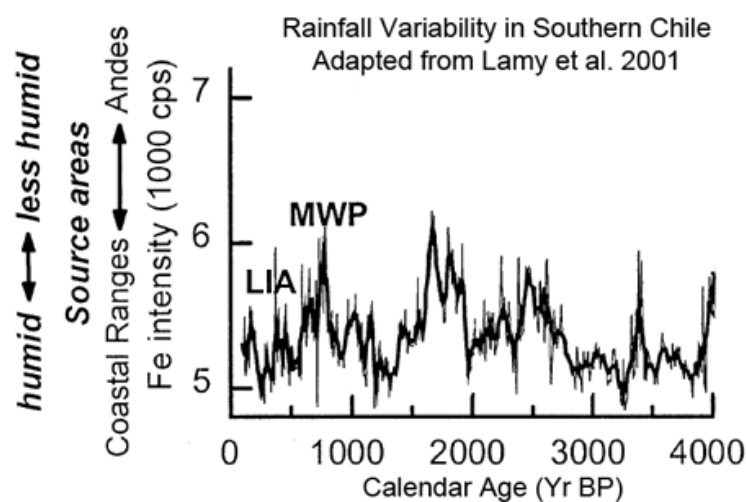


Figure 4.2.4.9.3.1. Reconstructed rainfall record for southern Chile. Adapted from Lamy, F., Hebbeln, D., Röhl, U., and Wefer, G. 2001. Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies. *Earth and Planetary Science Letters* 185: 369–382.

Observations: Temperature Records

microorganisms, alkenones, and organic (Corg content, molar C/N) and inorganic (Cinorg, Fe, Ti, Ca) elements as proxies for terrestrial input and/or carbonate productivity. They compared their findings with those of other researchers who had conducted similar paleoclimatic studies in various parts of South America and Antarctica.

The seven scientists reported, “the down-core record clearly shows two productivity/climate modes.” As they describe it, the first period—prior to 900 cal yr BP and including the Medieval Warm Period (MWP)—is characterized by “decreased marine productivity and a reduced continental signal, pointing to diminished precipitation and runoff.” The second period—between 750 cal yr BP and the late 1800s, and including the Little Ice Age (LIA)—is characterized by “elevated productivity and an increased continental signal, suggesting higher precipitation and runoff.” In addition, their data clearly show the MWP and LIA were “separated by a relatively abrupt transition of ~150 years.” In addition to providing another demonstration of the reality of the MWP and LIA in South America, the Chilean, German, and U.S. scientists conclude the good correspondence between their record and various “other paleoclimate studies carried out in South America and Antarctica demonstrates that the Chilean fjord area of Northern Patagonia is not just sensitive to local climatic variability but also to regional and possibly global variability.”

von Gunten *et al.* (2009) write, “quantitative high-resolution global, hemispherical and regional climate reconstructions covering the last millennium are fundamental in placing modern climate warming into a long-term context,” in order to “assess the sensitivity of the climate system to natural and anthropogenic forcings, and thus to reduce uncertainty about the magnitude and impact of future global climate change.” They note, for the entire Southern Hemisphere, “Mann and Jones (2003) considered only five data sets suitable for their work on surface temperature reconstructions for the past two millennia,” and “only two of these data series are from South America,” one of which is a tree-ring record “with unknown preservation of the low-frequency component of climate variability” and the other a $\delta^{18}\text{O}$ ice core record they describe as “arguably putative at best” in terms of its temperature signal.

von Gunten *et al.* developed a continuous high-resolution (1–3 years sampling interval, five-year filtered reconstruction) austral summer (December to

February) temperature reconstruction based on chloro-pigments derived from algae and phototrophic bacteria found in sediment cores retrieved from Central Chile’s Laguna Aculeo (33°50’S, 70°54’W) in 2005 that extended back to AD 850, which they describe as “the first quantitative temperature reconstruction for Central Chile for the last millennium.” The Swiss, German, and UK scientists report their data provided “quantitative evidence for the presence of a Medieval Climate Anomaly (in this case, warm summers between AD 1150 and 1350; $\Delta T = +0.27$ to $+0.37^\circ\text{C}$ with respect to (wrt) twentieth century) and a very cool period synchronous to the ‘Little Ice Age’ starting with a sharp drop between AD 1350 and AD 1400 ($-0.3^\circ\text{C}/10$ years, decadal trend) followed by constantly cool ($\Delta T = -0.70$ to -0.90°C wrt twentieth century) summers until AD 1750.”

The graph of their data, as presented in Figure 4.2.4.9.3.2, indicates the peak warmth of the Medieval Climate Anomaly was about 0.7°C warmer than the last decade or so of the twentieth century, but only about 0.25°C warmer than the peak warmth of the twentieth century, which occurred in the late 1940s in their reconstructed temperatures and their instrumental data, which are essentially identical over most of the 1900s. In addition, they note, the “structure of variability” shown in their data “is consistent in great detail with annually resolved tree-ring-based warm-season temperature and river discharge reconstructions from northern Patagonia for the past 400 years, with qualitative climate reconstructions from Andean glacier fluctuations, and with hydrological changes in Patagonian lake sediment records.”

The work of the five researchers thus clearly demonstrates the existence of both the Medieval Warm Period (MWP) and Little Ice Age in the Southern Hemisphere, as well as the fact that the MWP was warmer (and for much longer) than the Current Warm Period has been to date. This suggests there is nothing unnatural about the planet’s current level of warmth, or the rate at which it was reached, and thus removes any need to invoke current higher concentrations of atmospheric CO_2 as the cause of these nondescript features of our current climate.

Sepulveda *et al.* (2009) write, “deciphering climate variability in the Southern Hemisphere and particularly from southern South America—the only continental land mass lying between 38°S and the Antarctic Circle—is crucial for documenting the inter-hemispheric synchronicity of recent abrupt

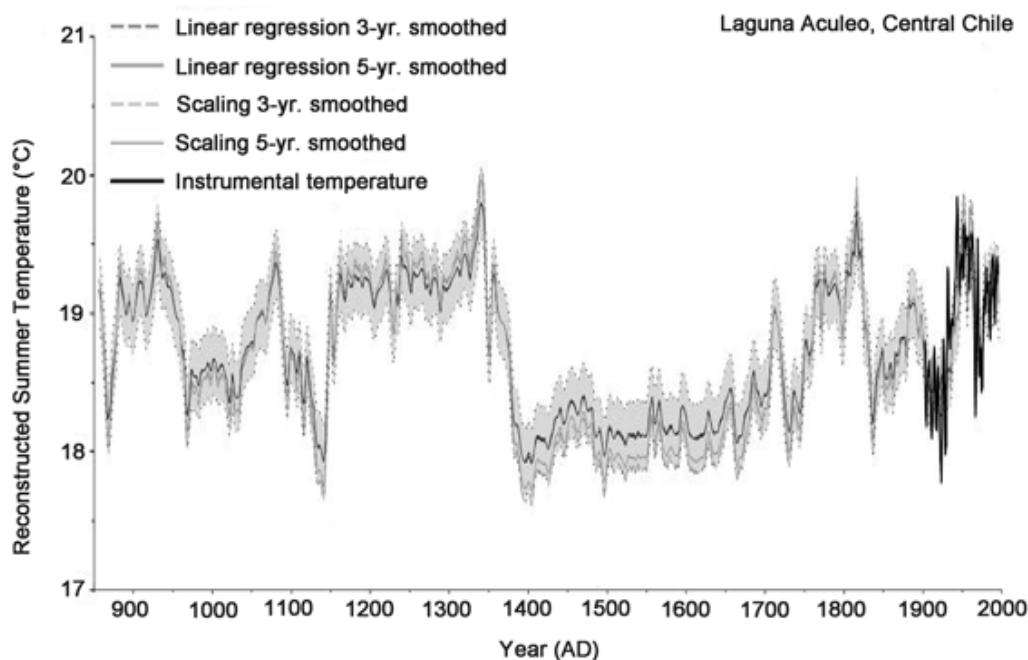


Figure 4.2.4.9.3.2. Proxy temperature reconstruction since AD 850 based on sedimentary pigments from a lake in central Chile. Adapted from von Gunten, L., Grosjean, M., Rein, B., Urrutia, R., and Appleby, P. 2009. A quantitative high-resolution summer temperature reconstruction based on sedimentary pigments from Laguna Aculeo, central Chile, back to AD 850. *The Holocene* **19**: 873–881.

climate changes and thereby determining their ultimate cause(s),” as well as for “predicting future abrupt climate changes.” The eight researchers conducted “a high-resolution multi-proxy study including the elemental and isotopic composition of bulk organic matter, land plant-derived biomarkers, and alkenone-based sea-surface temperature (SST) [derived] from a marine sedimentary record obtained from the Jacaf Fjord in northern Chilean Patagonia [44°20.00’S, 72°58.15’W]” to provide “a detailed reconstruction of continental runoff, precipitation and summer SST spanning the last 1750 years.”

The Chilean, German, and U.S. scientists report they “observed two different regimes of climate variability in [the] record: a relatively dry/warm period before 900 cal yr BP (higher runoff and average SST 1°C warmer than present day) and a wet/cold period after 750 cal yr BP (higher runoff and average SST 1°C colder than present day),” which they associate with the Medieval Warm Period and Little Ice Age, respectively. They conclude, “the reasonably good correlation between our results (particularly SST) and other continental and marine

archives from central-south Chile, Peru, and Antarctica ... confirms the occurrence of globally important climatic anomalies such as the Medieval Warm Period and the Little Ice Age.”

Solari *et al.* (2010) obtained a $\delta^{18}\text{O}$ record stretching back in time about 1,200 years from the shore of Lago Sarmiento (51°03’00”S, 72°45’01”W) in southern Chile, where massive dead carbonate microbialites are exposed, to which they applied a “well-established, temperature-dependent oxygen isotope equilibrium fractionation equation between calcite and water” that yielded values of surface water temperature at a number of dates, the two oldest of which (AD 800 and 1100) bracketed the MWP at that location. The warmest of these values was 9.5°C, which was 1.26°C greater than the mean surface water temperature of 8.24°C they calculated from actual temperature measurements made every 20 minutes from April 1, 2003 to March 15, 2004. A $\delta^{18}\text{O}$ -based surface water temperature of 8.9°C is indicated fairly close to the present. Calculated conservatively, the peak temperature of the MWP was likely 0.6°C greater than the peak of the CWP.

Observations: Temperature Records

Fletcher and Moreno (2012) “sampled and analyzed sediment cores from Laguna San Pedro (38°26’S, 71°19’W),” which they describe as “a small closed-basin lake located within the present-day distribution of *Araucaria-Nothofagus* forest in the Temperate-Mediterranean Transition zone in the Andes of Chile,” where they reconstructed the vegetation, climate, and fire regime histories of the past 1,500 years. They found evidence of “persistent cool/La Nina ENSO states” during the periods 1300–1000 and 725–121 cal yr BP, which they identify as the “Dark Ages Cold Period and Little Ice Age, respectively.” In addition, they report finding evidence of “low relative growing season moisture and warmer temperature that correspond well with evidence for persistent warm/El Nino ENSO states (1500–1300 and 1000–725 cal yr BP),” which they respectively associate with the Roman Warm Period and Medieval Climate Anomaly. Regarding the transition from the Little Ice Age to the Current Warm Period, which occurred from 121 cal yr BP (AD 1829) to the present, they found evidence for “a dramatic landscape alteration associated with the arrival of exotic taxa and an increase in burning,” which they attribute to European colonization of the area. Fletcher and Moreno also state, “the palaeo-environmental history inferred from Laguna San Pedro provides important palaeo-climatic information for this part of southern South America that is poorly represented in the palaeo-climate literature.”

Elbert *et al.* (2013) analyzed sediment cores from Laguna Escondida (45°31’S, 71°49’W) in Northern Chile for biogenic silica (bSi) concentrations, which they compared with modern meteorological data from the CRU TS 3.0 reanalysis data set (Mitchell and Jones, 2005; 0.5°x0.5° grid cell 45°S/72°W), while using radiometric dating (²¹⁰Pb, ¹³⁷Cs, ¹⁴C-MS) to place the entire set of results in a temporally correct perspective. The result is depicted in Figure 4.2.4.9.3.3, showing the peak warmth of the Medieval Warm Period (~AD 920–1180) was about 2.9°C greater than the most recent sediment-derived Current Warm Period temperatures.

References

Elbert, J., Wartenburger, R., von Gunten, L., Urrutia, R., Fischer, D., Fujak, M., Hamann, Y., Greber, N.D., and Grosjean, M. 2013. Late Holocene air temperature variability reconstructed from the sediments of Laguna Escondida, Patagonia, Chile (45°30’S). *Palaeogeography, Palaeoclimatology, Palaeoecology* **369**: 482–492.

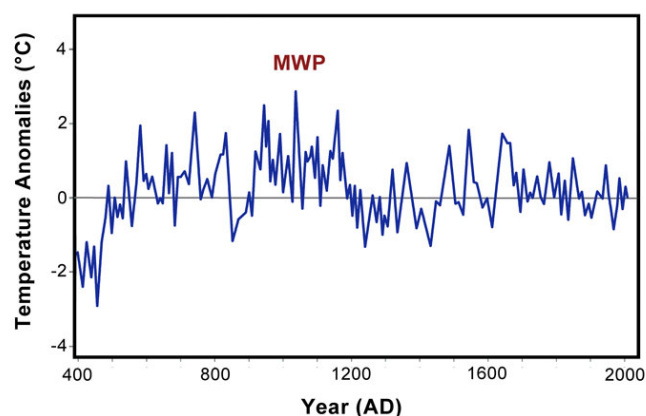


Figure 4.2.4.9.3.3. Proxy temperature reconstruction since AD 400 from a lake in northern Chile. Adapted from Elbert, J., Wartenburger, R., von Gunten, L., Urrutia, R., Fischer, D., Fujak, M., Hamann, Y., Greber, N.D., and Grosjean, M. 2013. Late Holocene air temperature variability reconstructed from the sediments of Laguna Escondida, Patagonia, Chile (45°30’S). *Palaeogeography, Palaeoclimatology, Palaeoecology* **369**: 482–492.

Fletcher, M.-S. and Moreno, P.I. 2012. Vegetation, climate and fire regime changes in the Andean region of southern Chile (38°S) covaried with centennial-scale climate anomalies in the tropical Pacific over the last 1500 years. *Quaternary Science Reviews* **46**: 46–56.

Jenny, B., Valero-Garces, B.L., Urrutia, R., Kelts, K., Veit, H., Appleby, P.G., and Geyh M. 2002. Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during the last 2000 years: The Laguna Aculeo record (33°50’S). *Quaternary International* **87**: 3–18.

Lamy, F., Hebbeln, D., Röhl, U., and Wefer, G. 2001. Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies. *Earth and Planetary Science Letters* **185**: 369–382.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 1–4.

Nester, P.L., Gayo, E., Latorre, C., Jordan, T.E., and Blanco, N. 2007. Perennial stream discharge in the hyper-arid Atacama Desert of northern Chile during the latest Pleistocene. *Proceedings of the National Academy of Sciences, USA* **104**: 19,724–19,729.

Rebolledo, L., Sepulveda, J., Lange, C.B., Pantoja, S., Bertrand, S., Huguen, K., and Figueroa, D. 2008. Late Holocene marine productivity changes in Northern Patagonia-Chile inferred from a multi-proxy analysis of Jacaf channel sediments. *Estuarine, Coastal and Shelf Science* **80**: 314–322.

Rein B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

Sepulveda, J., Pantoja, S., Hughen, K.A., Bertrand, S., Figueroa, D., Leon, T., Drenzek, N.J., and Lange, C. 2009. Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jacaf Fjord, 44°S). *Quaternary Research* **72**: 400–409.

Solari, M.A., Herve, F., Le Roux, J.P., Airo, A., and Sial, A.N. 2010. Paleoclimatic significance of lacustrine microbialites: A stable isotope case study of two lakes at Torres del Paine, southern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology* **297**: 70–82.

von Gunten, L., Grosjean, M., Rein, B., Urrutia, R., and Appleby, P. 2009. A quantitative high-resolution summer temperature reconstruction based on sedimentary pigments from Laguna Aculeo, central Chile, back to AD 850. *The Holocene* **19**: 873–881.

4.2.4.9.4 Peru

Chepstow-Lusty *et al.* (1998) derived a 4,000-year climate history from a study of pollen in sediment cores obtained from a recently in-filled lake in the Patacancha Valley near Marcacocha. Their data indicate a several-century decline in pollen content after AD 100, as the Roman Warm Period gave way to the Dark Ages Cold Period. A “more optimum climate,” as they describe it, with warmer temperatures and drier conditions, prevailed for several centuries after about AD 900, the Medieval Warm Period, followed by the Little Ice Age. These climatic periods are in nearly perfect temporal agreement with the climate history derived by McDermott *et al.* (2001) from a study of a stalagmite recovered from a cave nearly half the world away in Ireland.

Subsequent work in this area was conducted by Chepstow-Lusty and Winfield (2000). They identify “the warm global climatic interval frequently referred to as the Medieval Warm Epoch” centered on approximately 1,000 years ago. This extremely arid interval in this part of South America, in their opinion, may have played a significant role in the collapse of the Tiwanaku civilization further south, where a contemporaneous prolonged drought occurred in and around the area of Lake Titicaca (Binford *et al.*, 1997; Abbott *et al.*, 1997).

Near the start of this extended dry period, which established itself gradually between about AD 700 and 1000, Chepstow-Lusty and Winfield report,

“temperatures were beginning to increase after a sustained cold period that had precluded agricultural activity at these altitudes.” This earlier colder and wetter interval was coeval with the Dark Ages Cold Period of the North Atlantic region, which in the Peruvian Andes prevailed for much of the millennium preceding AD 1000, as revealed by a series of climatic records developed from sediment cores extracted from other lakes in the Central Peruvian Andes (Hansen *et al.*, 1994) and by proxy evidence of concomitant Peruvian glacial expansion (Wright, 1984; Seltzer and Hastorf, 1990).

Preceding the Dark Ages Cold Period in both parts of the world was what in the North Atlantic region is called the Roman Warm Period. This well-defined climatic epoch is also strikingly evident in the pollen records of Chepstow-Lusty *et al.* (2003), straddling the BC/AD calendar break with one to two hundred years of relative warmth and significant aridity on both sides of it.

Data compiled by Chepstow-Lusty *et al.* (2003) reveal the occurrence of the Little Ice Age, which in the Central Peruvian Andes was characterized by relative coolness and wetness. These characteristics of that climatic interval are also evident in ice cores retrieved from the Quelccaya ice cap in southern Peru, the summit of which extends 5,670 meters above mean sea level (Thompson *et al.*, 1986, 1988). Both the Quelccaya ice core data and the Marcacocha pollen data indicate the transition to the drier Current Warm Period that occurred over the past 100-plus years.

Rein *et al.* (2004) derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima. They found a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the Medieval period. They report, “lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250” (see Figure 4.2.4.9.4.1). They write, “all known terrestrial deposits of El Niño mega-floods (Magillan and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly.” In addition, “this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain,” citing 11 references in support of this statement.

Consequently, because heavy winter rainfalls

Observations: Temperature Records

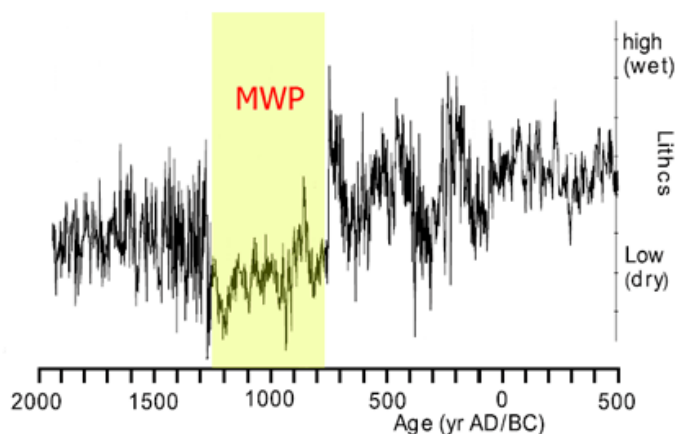


Figure 4.2.4.9.4.1. Marine record of El Niño flood sediments off Peru, as derived from lithic concentrations. Adapted from Rein B., Lückge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* 31: 10.1029/2004GL020161.

along and off coastal Peru occur only during times of maximum El Niño strength, and because El Niños are typically more prevalent and stronger during cooler as opposed to warmer periods, the lack of strong El Niños from A.D. 800 to 1250 suggests this period was truly a Medieval Warm Period. The significance of this observation was not lost on Rein *et al.* In the introduction to their paper, for example, they observe, “discrepancies exist between the Mann curve and alternative time series for the Medieval period.” Most notably, they write, “the global Mann curve has no temperature optimum, whereas the Esper *et al.* (2002) reconstruction shows northern hemisphere temperatures almost as high as those of the 20th century” during the Medieval Warm Period. Rein *et al.* conclude, “the occurrence of a Medieval climatic anomaly (A.D. 800–1250) with persistently weak El Niños may therefore assist the interpretation of some of the regional discrepancies in thermal reconstructions of Medieval times,” a polite way of

suggesting the Mann *et al.* (1998, 1999) hockey stick temperature history is deficient in failing to identify a true Medieval Warm Period.

Rein *et al.* (2005) derived sea surface temperatures from alkenones extracted from a high-resolution marine sediment core retrieved off the coast of Peru (12.05°S, 77.66°W), spanning the past 20,000 years and ending in the 1960s. Their Figure 11, reproduced here as Figure 4.2.4.9.4.2, shows the warmest temperatures of this 20,000 year period (~23.2°C) occurred during the late Medieval time (AD 800–1250). Taking this value, 23.2°C, and comparing it with the modern monthly long-term means in sea surface temperature, which the authors characterize as between 15°C and 22°C, the peak warmth of the Medieval Warm Period for this region was about 1.2°C above that of the Current Warm Period.

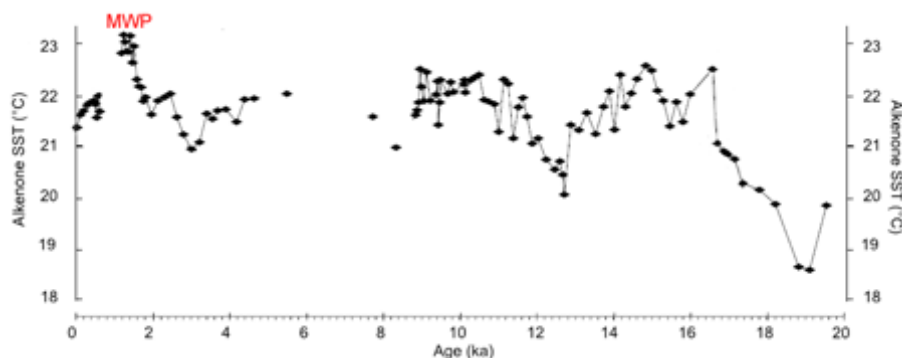


Figure 4.2.4.9.4.2. Coastal Peru proxy sea surface temperatures. Adapted from Rein B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., and Dullo, W.-C. 2005. El Niño variability off Peru during the last 20,000 years. *Paleoceanography* 20: 10.1029/2004PA001099.

Sterken *et al.* (2006) conducted a quantitative diatom analysis on a sediment core obtained from the small infilled lake basin of Marcacocha, in the Cuzco region of the south central Andes mountains of Peru (13.22°S, 72.2°W) to reconstruct environmental changes during the past 1,200 years. The data indicated a major climate transition around AD 1070, representing “the most prominent change in the diatom record with a marked shift towards higher temperatures.”

Unkel *et al.* (2007) employed “geomorphological field-work” and “chronometric analyses”—consisting of conventional ^{14}C -dating of charcoal, wood and root samples and optical-stimulated luminescence dating of feldspar and quartz—while investigating “alluvial archives and debris flow deposits” in the hyper-arid zone of the northern Atacama Desert of Peru between Pisco/Ica and Nazca/San Juan ($\sim 14.3^\circ\text{S}$, 75.3°W). This work, together with others’, indicates the existence of a period of “fluvial silence” for “the time of the 9th-13th centuries,” due to “increased aridification,” which they associated with the Medieval Warm Period ($\sim\text{AD } 800\text{--}1250$).

Bird *et al.* (2011) developed a 2,300-year history of the South American Summer Monsoon (SASM) from an annually resolved authigenic calcite record of precipitation $\delta^{18}\text{O}$ obtained from a varved lake in the Central Peruvian Andes—Laguna Pumacocha (10.70°S , 76.06°W , 4300 m asl). Their history shows, they write, “ $\delta^{18}\text{O}$ peaked during the Medieval Climate Anomaly (MCA) from AD 900 to 1100, providing evidence the SASM weakened considerably during this period.” Thereafter, they found, “minimum $\delta^{18}\text{O}$ values occurred during the Little Ice Age (LIA) between AD 1400 and 1820, reflecting a prolonged intensification of the SASM,” after which “ $\delta^{18}\text{O}$ increased rapid-ly, particularly during the Current Warm Period (CWP; AD 1900 to present), indicating a return to reduced SASM precipitation.”

The six scientists also note the Pumacocha record tracks the 900-year-long Cascayunga Cave $\delta^{18}\text{O}$ record (6.09°S , 77.23°W , 930 m asl), which they say “is interpreted as a record of South American rainfall (Reuter *et al.*, 2009).” They report it shares many features with the annually resolved Quelccaya Ice Cap $\delta^{18}\text{O}$ record (13.93°S , 70.83°W , 5670 m asl) derived by Thompson *et al.* (1986). They state, “the close agreement in the timing, direction, and magnitude of mean state changes in $\delta^{18}\text{O}$ during the MCA, LIA, and CWP from lake sediment, speleothem, and ice core records supports the idea that a common large-scale mechanism influenced $\delta^{18}\text{O}$ reaching these central Andean sites spanning 11° latitude and 4,740 meters of elevation.” They conclude, “the most likely cause of these documented shifts in $\delta^{18}\text{O}_{\text{precip}}$ is a change in SASM intensity, as all three sites receive the majority of their annual precipitation during the monsoon season.”

Bird *et al.* also describe the “remarkable correspondence” that exists between the Pumacocha $\delta^{18}\text{O}$ record of SASM rainfall and the 2,000-year Northern Hemispheric temperature reconstruction of

Moberg *et al.* (2005), plus the similar relationship both records share with the somewhat-shorter North Atlantic temperature reconstruction of Mann *et al.* (2009). Specifically, they indicate “the two greatest reductions in SASM intensity in the Pumacocha $\delta^{18}\text{O}$ record were coincident with Northern Hemisphere temperature maxima during the MCA and CWP,” and “the SASM was stronger than at any other point in the last 2,300 years when Northern Hemisphere temperatures were at a 2,000-year low during the LIA.” As noted above, their data show the same relationships exist between the Pumacocha $\delta^{18}\text{O}$ history and the North Atlantic temperature history.

Especially interesting about these observations is that Bird *et al.*’s graphical representations of the Northern Hemisphere and North Atlantic temperature histories of Moberg *et al.* and Mann *et al.* both show the peak warmth of the MCA to be at least as great as, and possibly even a little greater than, the peak warmth of the CWP, plus the fact that the $\delta^{18}\text{O}$ data of Bird *et al.* suggest much the same thing, based upon what they call the “remarkable correspondence” among the three datasets, which can be seen in Figure 4.2.4.9.4.3.

As illustrated in this figure, the correspondence among the four datasets is nothing short of astounding. The equivalent or slightly greater warmth of the MCA (known also as the Medieval Warm Period or MWP) compared to the CWP would appear to be well-established for the North Atlantic Ocean, the Northern Hemisphere, and a good portion of South America. In support of this conclusion, Bird *et al.* note the diminished SASM precipitation (higher $\delta^{18}\text{O}$ data) during the MWP and CWP also tracks the northward migration of the Intertropical Convergence Zone over the Atlantic, since “the Pumacocha record shows that the SASM was considerably reduced during the MCA when peak %Ti in the Cariaco Basin record indicates that the Intertropical Convergence Zone was persistently northward,” as demonstrated by Haug *et al.* (2001).

A growing body of evidence suggests the Medieval Warm Period of a thousand or so years ago was as warm as or warmer than the Current Warm Period to date. And with the air’s CO_2 concentration having risen by some 40 percent since the days of the MWP, without any net increase in temperature, it is unlikely Earth’s current warmth is being provided by that increase in the atmosphere’s CO_2 content.

Observations: Temperature Records

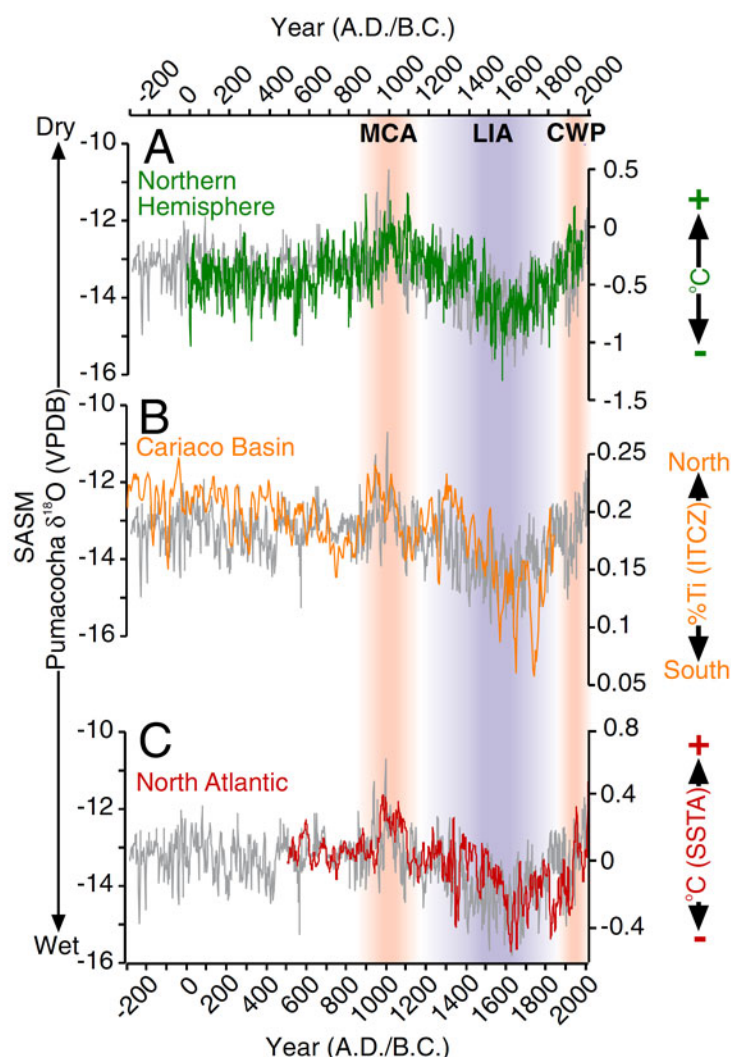


Figure 4.2.4.9.4.3. (A) The reconstructed Northern Hemispheric temperature history of Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617; (B) the reconstructed North Atlantic temperature history of Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**: 1256–1260; and (C) the Cariaco Basin %Ti data of Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Rohl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293**: 1304–1308, which represent the degree of northward migration of the Intertropical Convergence Zone, each plotted together with the $\delta^{18}O$ data (gray lines) of Bird *et al.* (2011). Figure adapted from Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D., and Rosenmeier, M.F. 2011. A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences USA* **108**: 8583–8588.

References

- Abbott, M.B., Binford, M.W., Brenner, M., and Kelts, K.R. 1997. A 3500 ^{14}C yr high resolution record of water-level changes in Lake Titicaca. *Quaternary Research* **47**: 169–180.
- Binford, M.W., Kolata, A.L., Brenner, M., Janusek, J.W., Seddon, M.T., Abbott, M., and Curtis, J.H. 1997. Climate variation and the rise and fall of an Andean civilization. *Quaternary Research* **47**: 235–248.
- Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D., and Rosenmeier, M.F. 2011. A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences USA* **108**: 8583–8588.
- Chepstow-Lusty, A.J., Bennett, K.D., Fjeldsa, J., Kendall, A., Galiano, W., and Herrera, A.T. 1998. Tracing 4,000 years of environmental history in the Cuzco Area, Peru, from the pollen record. *Mountain Research and Development* **18**: 159–172.
- Chepstow-Lusty, A., Frogley, M.R., Bauer, B.S., Bush, M.B., and Herrera, A.T. 2003. A late Holocene record of arid events from the Cuzco region, Peru. *Journal of Quaternary Science* **18**: 491–502.
- Chepstow-Lusty, A. and Winfield, M. 2000. Inca agroforestry: lessons from the past. *Ambio* **29**: 322–328.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Hansen, B.C.S., Seltzer, G.O., and Wright Jr., H.E. 1994. Late Quaternary vegetational change in the central Peruvian Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **109**: 263–285.
- Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Rohl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293**: 1304–1308.
- Magillan, F.J. and Goldstein, P.S. 2001. El Niño floods and culture change: A late Holocene flood history for the Rio Moquegua, southern Peru. *Geology* **29**: 431–434.
- Mann, M.E., Bradley, R.S., and Hughes, M.K.

1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**: 1256–1260.

McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Rein B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., and Dullo, W.-C. 2005. El Niño variability off Peru during the last 20,000 years. *Paleoceanography* **20**: 10.1029/2004PA001099.

Rein B., Lückge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

Reuter, J., Stott, L., Khidir, D., Sinha, A., Cheng, H., and Edwards, R.L. 2009. A new perspective on the hydroclimate variability in northern South America during the Little Ice Age. *Geophysical Research Letters* **36**: 10.1029/2009GL041051.

Seltzer, G. and Hastorf, C. 1990. Climatic change and its effect on Prehispanic agriculture in the central Peruvian Andes. *Journal of Field Archaeology* **17**: 397–414.

Sterken, M., Sabbe, K., Chepstow-Lusty, A., Frogley, M., Vanhoutte, K., Verleyen, E., Cundy, A., and Vyverman, W. 2006. Hydrological and land-use changes in the Cuzco region (Cordillera Oriental, South East Peru) during the last 1200 years: a diatom-based reconstruction. *Archiv für Hydrobiologie* **165**: 289–312.

Thompson, L.G., Davis, M.E., Mosley-Thompson, E., and Liu, K.-B. 1988. Pre-Incan agricultural activity recorded in dust layers in two tropical ice cores. *Nature* **307**: 763–765.

Thompson, L.G., Mosley-Thompson, E., Dansgaard, W., and Groote, P.M. 1986. The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya ice cap. *Science* **234**: 361–364.

Unkel, I., Kadereit, A., Machtle, B., Eitel, B., Kromer, B., Wagner, G., and Wacker, L. 2007. Dating methods and

geomorphic evidence of paleoenvironmental changes at the eastern margin of the South Peruvian coastal desert (14°30'S) before and during the Little Ice Age. *Quaternary International* **175**: 3–28.

Wells, L.E. 1990. Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru. *Geology* **18**: 1134–1137.

Wright Jr., H.E. 1984. Late glacial and Late Holocene moraines in the Cerros Cuchpanga, central Peru. *Quaternary Research* **21**: 275–285.

4.2.4.9.5 Venezuela

Haug *et al.* (2001) found a temperature/precipitation relationship for Venezuela different from that of the rest of the continent. In examining the titanium and iron concentrations of an ocean sediment core taken from the Cariaco Basin on the country's northern shelf, they determined the concentrations of these elements were lower during the Younger Dryas cold period between 12.6 and 11.5 thousand years ago, corresponding to a weakened hydrologic cycle with less precipitation and runoff. During the warmth of the Holocene Optimum of 10.5 to 5.4 thousand years ago, they found, titanium and iron concentrations remained at or near their highest values, suggesting wet conditions and an enhanced hydrologic cycle. Closer to the present, higher precipitation also was noted during the Medieval Warm Period from 1.05 to 0.7 thousand years ago, followed by drier conditions associated with the Little Ice Age between 550 and 200 years ago.

Haug *et al.* (2003) developed a hydrologic history of pertinent portions of the record, which yielded “roughly bi-monthly resolution and clear resolution of the annual signal.” According to this record, “before about 150 A.D.,” which the climate history of McDermott *et al.* (2001) shows as corresponding to the latter portion of the Roman Warm Period (RWP), Mayan civilization flourished. During the transition to the Dark Ages Cold Period (DACP), which was accompanied by a slow but long decline in precipitation, “the first documented historical crisis hit the lowlands, which led to the ‘Pre-Classic abandonment’ (Webster, 2002) of major cities,” Haug *et al.* report.

This crisis occurred during the first intense multi-year drought of the RWP-to-DACP transition, which was centered on about the year 250 AD. Although the drought was devastating to the Maya, when it was over, “populations recovered, cities were reoccupied,

Observations: Temperature Records

and Maya culture blossomed in the following centuries during the so-called Classic period,” Haug *et al.* report. Between about 750 and 950 AD, during what Haug *et al.* determined was the driest interval of the entire Dark Ages Cold Period, “the Maya experienced a demographic disaster as profound as any other in human history” in response to a number of intense multi-year droughts. During this Terminal Classic Collapse, as it is called, “many of the densely populated urban centers were abandoned permanently, and Classic Maya civilization came to an end.”

Haug *et al.* conclude the latter droughts “were the most severe to affect this region in the first millennium A.D.” Although some of these spectacular droughts were “brief,” lasting “only” between three and nine years, Haug *et al.* report “they occurred during an extended period of reduced overall precipitation that may have already pushed the Maya system to the verge of collapse.

Although the Mayan civilization thus faded away, Haug *et al.*’s data soon thereafter depict the development of the Medieval Warm Period, when the Vikings established their historic settlement on Greenland. Then came the Little Ice Age, which just as quickly led to the Vikings’ demise in that part of the world. This distinctive cold interval of the planet’s millennial-scale climatic oscillation must have also led to hard times for the people of Mesoamerica and northern tropical South America, for the data of Haug *et al.* indicate the Little Ice Age produced by far the lowest precipitation regime (of several hundred years duration) of the last two millennia in that part of the world.

Goni *et al.* (2004) reconstructed a history of sea surface temperatures covering the past 6,000 years for the Cariaco Basin (20°30’N, 64°40’W) on the continental shelf off the central coast of Venezuela, based on the degree of un-saturation of certain long-chain alkenones synthesized by haptophyte algae contained in a sediment core retrieved from the eastern sub-basin.

Figure 4.2.4.9.5.1 shows the highest alkenone-

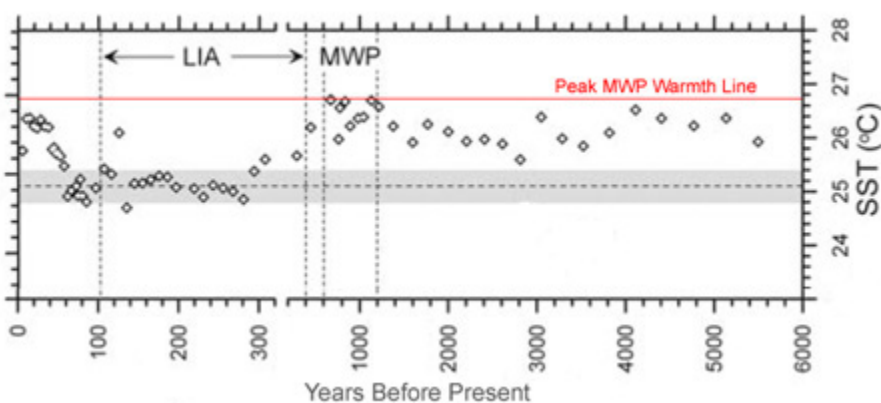


Figure 4.2.4.9.5.1. Alkenone-based SST reconstruction for the Cariaco Basin, Venezuela. Adapted from Goni, M.A., Woodworth, M.P., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Muller-Karger, F., Astor, Y., and Varela, R. 2004. Generation, transport, and preservation of the alkenone-based U37^K sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela). *Global Biogeochemical Cycles* **18**: 10.1029/2003GB002132.

derived sea surface temperatures “were measured during the Medieval Warm Period (MWP),” which Goni *et al.* identify as occurring between AD 800 and 1400. It is also evident peak MWP temperatures were approximately 0.35°C warmer than peak Current Warm Period (CWP) temperatures and fully 0.95°C warmer than the mean temperature of the last decade of the twentieth century.

Rein (2004) obtained high-resolution $\delta^{18}\text{O}$ records generated from seasonally representative planktic foraminifera from two ocean sediment cores extracted from the Cariaco Basin off the coast of Venezuela (~10.65°N, 64.66°W) to produce a temperature/salinity reconstruction in this region of the Caribbean/tropical North Atlantic over the last 2,000 years. A general trend toward cooler and perhaps more saline waters over the length of the record was observed. The authors describe discussion of the Medieval Warm Period and Little Ice Age as “complicated,” but they acknowledge their record reveals “an interval of warmer [sea surface temperatures] prior to ~ A.D. 1600–1900” where the $\delta^{18}\text{O}$ data “correctly sequence the relative temperature change between the so-called MWP and LIA.”

According to the authors’ graph of *G. bulloides* $\delta^{18}\text{O}$ (25-year mean, reproduced here as Figure 4.2.4.9.5.2), along with their stated relationship that a $\delta^{18}\text{O}$ change of 1.0‰ is equivalent to a 4.2°C change in temperature, the difference in peak warmth between the MWP and CWP can be calculated as 1.05°C, with the MWP being the warmer of the two

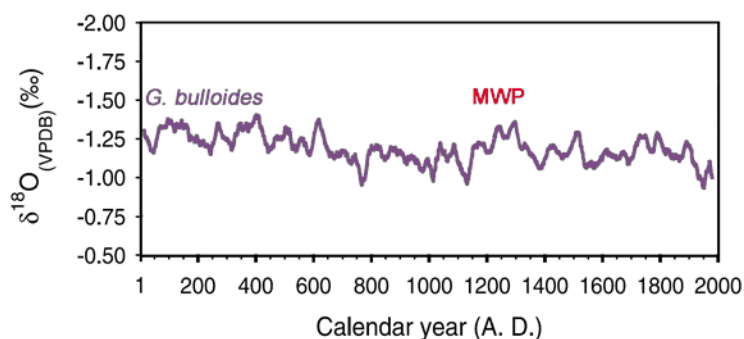


Figure 4.2.4.9.5.2. A high-resolution $\delta^{18}\text{O}$ temperature/salinity reconstruction from two ocean sediment cores extracted from the Cariaco Basin off the coast of Venezuela. Adapted from Black, D.E., Thunell, R.C., Kaplan, A., Peterson, L.C., and Tappa, E. J. 2004. A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability. *Paleoceanography* **19**, PA2022, doi:10.1029/2003PA000982.

periods.

Polissar *et al.* (2006) derived continuous decadal-scale records of two climate-relevant parameters related to precipitation/ evaporation balance and, hence, glacier activity, from sediment cores extracted from Laguna Blanca (8°20'N, 71°47'W) and Laguna Mucubaji (8°47'N, 70°50'W). Data they obtained from the nearby Piedras Blancas peat bog yielded a third parameter—"pollen histories that chronicle vegetation change in response to climate." All three parameters suggest the MWP was warmer than the CWP.

In the case of Laguna Blanca magnetic susceptibility, the MWP's greater warmth extended from before the start of the record (sometime prior to AD 500) to approximately AD 1300. In the case of the abundance of sedge pollen from the Piedras Blancas peat bog, it extended from about AD 550 to 1020, and in the case of altitudinal shifts in ecological zones derived from the Piedras Blancas data, it extended from sometime before the start of the record to about AD 1000. All three datasets thus suggest the MWP, during the period AD 550–1000, was warmer than the CWP.

The Polissar *et al.* study also clearly implicated solar variability as the cause of the climatic variations they observed. The six scientists note, for example, "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima," and they note the data they presented "suggest that solar activity has exerted a strong influence on century-

scale tropical climate variability during the late Holocene, modulating both precipitation and temperature," in addition to demonstrating the "considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability."

References

- Black, D.E., Thunell, R.C., Kaplan, A., Peterson, L.C., and Tappa, E. J. 2004. A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability. *Paleoceanography* **19**, PA2022, doi:10.1029/2003PA000982.
- Goni, M.A., Woodworth, M.P., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Muller-Karger, F., Astor, Y., and Varela, R. 2004. Generation, transport, and preservation of the alkenone-based U37^{K} sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela). *Global Biogeochemical Cycles* **18**: 10.1029/2003GB002132.
- Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., and Aeschlimann, B. 2003. Climate and the collapse of Maya civilization. *Science* **299**: 1731–1735.
- Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Rohl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293**: 1304–1308.
- McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.
- Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., and Bradley, R.S. 2006. Solar modulation of Little Ice Age climate in the tropical Andes. *Proceedings of the National Academy of Sciences*: 10.1073/pnas.0603118103.
- Webster, D. 2002. *The Fall of the Ancient Maya*. Thames and Hudson, London, UK.

4.2.4.9.6 Other/Multiple Regions

Kellerhals *et al.* (2010) write, "to place recent global warming into a longer-term perspective and to understand the mechanisms and causes of climate change, proxy-derived temperature estimates are needed for time periods prior to instrumental records and regions outside instrumental coverage." They also note "for tropical regions and the Southern

Observations: Temperature Records

Hemisphere ... proxy information is very fragmentary.”

Kellerhals *et al.* developed “a reconstruction of tropical South American temperature anomalies over the last ~1600 years ... based on a highly resolved and carefully dated ammonium record from an ice core that was drilled in 1999 on Nevado Illimani [16°37'S, 67°46'W] in the eastern Bolivian Andes.” The researchers note “studies from other remote ice core sites have found significant correlations between NH_4^+ concentration and temperature for Siberia and the Indian subcontinent for preindustrial time periods,” citing the work of Kang *et al.* (2002) and Eichler *et al.* (2009). In calibrating and validating the NH_4^+ -to-°C transfer function, they say they used “the Amazon Basin subset of the gridded HadCRUT3 temperature data set,” described by Brohan *et al.* (2006).

The results of this analysis are depicted in Figure 4.2.4.9.6.1. The scientists report, “the most striking features in the reconstruction are [1] the warm temperatures from ~1050 to ~1300 AD [the Medieval Warm Period] compared to the preceding and following centuries, [2] the persistent cooler temperatures from ~1400 to ~1800 AD [the Little Ice Age], and [3] the subsequent rise to warmer temperatures [the Current Warm Period] which eventually seem to exceed, in the last decades of the 20th century, the range of past variation.” In regard to this last observation—as best as can be determined from their graph of the data—the peak warmth of the Current Warm Period was ~0.27°C greater than the peak warmth of the Medieval Warm Period.

Kellerhals *et al.* note the terms Little Ice Age (LIA) and Medieval Warm Period (MWP) can be validly employed to describe the “extensive advances of alpine glaciers in Europe from the 16th to the 19th century and the comparatively warm conditions in Europe from the 10th to the 13th century.” However, they add, the implication that these terms represent “globally synchronous cold and warm periods” has been dismissed by the IPCC and others. Kellerhals *et al.* conclude the “relatively warm temperatures during the first centuries of the past millennium and subsequent cold conditions from the 15th to the 18th century suggest that the MWP and the LIA are not confined to high northern latitudes,” and they “also have a tropical signature.” These observations add to the growing body of evidence demonstrating the

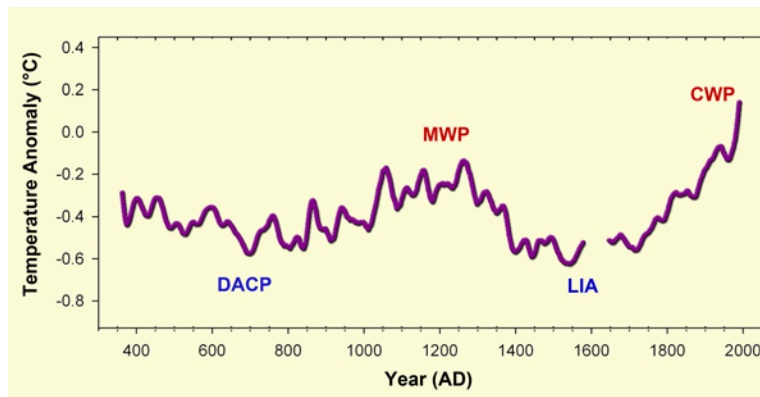


Figure 4.2.4.9.6.1. Reconstructed tropical South American temperature anomalies normalized to the AD 1961–1990 average and smoothed with a 39-year Gaussian filter. Adapted from Kellerhals, T., Brutsch, S., Sigl, M., Knusel, S., Gaggeler, H.W., and Schwikowski, M. 2010. Ammonium concentration in ice cores: a new proxy for regional temperature reconstruction? *Journal of Geophysical Research* **115**: 10.1029/2009JD012603.

global extent of the millennial-scale oscillation of climate that produced both the MWP and the LIA, and which has likely been responsible for the bulk of the warming that led to the establishment of the Current Warm Period.

Neukom *et al.* (2011) reconstructed a mean austral summer (December–February) temperature history for the period AD 900–1995 for the terrestrial area of the planet located between 20°S and 55°S and between 30°W and 80°W—a region they call Southern South America (SSA)—using 22 of the best climate proxies they could find that stretched far enough back in time. Their results, they note, “represent the first seasonal sub-continental-scale climate field reconstructions of the Southern Hemisphere going so far back in time.” Such an analysis, the authors state, was necessary “to put the recent warming into a larger temporal and spatial context.”

According to the international research team—composed of scientists from Argentina, Chile, Germany, Switzerland, The Netherlands, the United Kingdom, and the United States—their summer temperature reconstruction indicates “a warm period extended in SSA from 900 (or even earlier) to the mid-fourteenth century,” which they describe as having been “towards the end of the Medieval Climate Anomaly as concluded from Northern Hemisphere temperature reconstructions.” As depicted in Figure 4.2.4.9.6.2, their calculations show

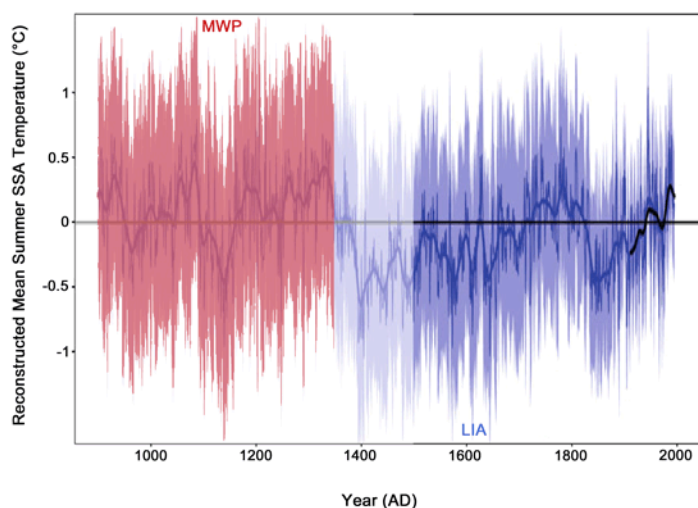


Figure 4.2.4.9.6.2. Reconstructed mean summer SSA temperatures. Adapted from Neukom, R., Luterbacher, J., Villalba, R., Kuttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.-C., Black, D.E., Christie, D.A., D'Arrigo, R., Lara, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urritia, R., and von Gunten, L. 2011. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* 37: 35–51.

the warmest decade of this Medieval Warm Period was AD 1079–1088, which, as best as can be determined from their graph, is about 0.17°C warmer than the peak warmth of the Current Warm Period.

Bracco *et al.* (2011) studied the emergence and development of prehistoric mound building in southeast Uruguay, employing paleoclimatic data to obtain a picture of how the climate of the region changed in the past 7,000 years. Focusing on the coastal lagoons within the Merin Lagoon basin, located between 31–34°S and 52–54°W in the easternmost part of the South American plains, Bracco *et al.* say paleolimnological investigations were initiated there in AD 2000 by a multidisciplinary group of researchers who studied past climate conditions via “multiproxy analyses (i.e., diatoms, opal phytoliths, pollen, molluscs, sediments, geochemistry, thin sections), together with radiocarbon dating.” Working predominantly with phytoliths found in various sediment cores, they derived 7,000-year histories of both temperature and a humidity index.

The South American scientists found a period (AD 750–1350) “characterized by warmer and wetter conditions than those of the present,” which matches well with the timeframe of the Medieval Warm

Period. Within this period, they write, “there are two peaks of extreme humid and warm events,” the second of which “fits chronologically into the ‘Warm Period’ (Broecker, 2001; Roberts, 2009), whose occurrence has been already pointed out by Iriondo and Garcia (1993) and Prevosti *et al.* (2004) in this region.”

These findings help confirm the global nature of the Medieval Warm Period. Bracco *et al.* also note their results “are consistent with other paleoclimatic reconstructions (Bracco *et al.*, 2005; Garcia-Rodriguez *et al.*, 2009) and the synthesis presented by Mancini *et al.* (2005), and they are partially consistent with other regional studies (Iriondo and Garcia, 1993; Prieto, 1996, 2000; Iriondo, 1999; Panario and Gutierrez, 1999; Tonni *et al.*, 1999; Zarate *et al.*, 2000; Prieto *et al.*, 2004; Quattrocchio *et al.*, 2008; Piovano *et al.*, 2009, in Argentina; Behling, 1995, 2002, 2007; Melo *et al.*, 2003; Moro *et al.*, 2004, in Brazil.” This growing body of empirical findings is evidence of the millennial-scale cycling of our planet’s climate, which after the passing of the Little

Ice Age that followed the Medieval Warm Period is likely what has most recently ushered us into the Current Warm Period.

References

- Behling, H. 1995. Late Quaternary environmental history from 5 new sites in the Brazilian tropics. *Abstracts, 14th INQUA Congress*, Berlin, Germany, p. 25.
- Behling, H. 2002. South and Southeast Brazilian grasslands during Late Quaternary times: a synthesis. *Paleogeography, Palaeoclimatology, Palaeoecology* 177: 19–27.
- Behling, H. 2007. Late Quaternary vegetation, fire and climate dynamics of Serra do Aracatuba in the Atlantic coastal mountains of Parana State, southern Brazil. *Vegetation, History and Archaeobotany* 16: 77–85.
- Bracco, R., del Puerto, L., Inda, H., and Castineira, C. 2005. Middle-late Holocene cultural and environmental dynamics in the east of Uruguay. *Quaternary International* 132: 37–45.
- Bracco, R., del Puerto, L., Inda, H., Panario, D., Castineira, C., and Garcia-Rodriguez, F. 2011. The relationship between emergence of mound builders in SE Uruguay and climate change inferred from opal phytolith records. *Quaternary International* 245: 62–73.

Observations: Temperature Records

- Broecker, W. 2001. Was the Medieval Warm Period global? *Science* **291**: 1497–1499.
- Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B., and Jones, P.D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research* **111**: 10.1029/2005JD006548.
- Eichler, A., Brutsch, S., Olivier, S., Papina, T., and Schwikowski, M. 2009. A 750-year ice core record of past biogenic emissions from Siberian boreal forests. *Geophysical Research Letters* **36**: 10.1029/2009GL038807.
- Garcia-Rodriguez, F., Piovano, E., del Puerto, L., Inda, H., Stutz, S., Bracco, R., Panario, D., Cordoba, F., Sylvestre, F., and Ariztegui, D. 2009. South American lake paleo-records across the Pampean Region. *PAGES News* **17**: 115–117.
- Iriondo, M. 1999. Climate changes in the South American plains: record of a continent-scale oscillation. *Quaternary International* **57/58**: 93–112.
- Iriondo, M. and Garcia, N. 1993. Climate variation in the Argentine plains during the last 18,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* **101**: 209–220.
- Kang, S.C., Mayewski, P.A., Qin, D., Yan, Y., Zhang, D., Hou, S., and Ren, J. 2002. Twentieth century increase of atmospheric ammonia recorded in Mount Everest ice core. *Journal of Geophysical Research* **107**: 10.1029/2001JD001413.
- Kellerhals, T., Brutsch, S., Sigl, M., Knusel, S., Gaggeler, H.W., and Schwikowski, M. 2010. Ammonium concentration in ice cores: a new proxy for regional temperature reconstruction? *Journal of Geophysical Research* **115**: 10.1029/2009JD012603.
- Mancini, M., Paez, M.M., Prieto, A.R., Stutz, S., Tonello, M., and Vilanova, I. 2005. Mid-Holocene climate variability reconstruction from pollen records (32°–52°S, Argentina). *Quaternary International* **132**: 47–59.
- Melo, M.S., Giannini, P.C.F., Pessenda, L.C., and Brandt Neto, M. 2003. Holocene paleoclimatic reconstruction based on the Lagoa Dourada deposits, southern Brazil. *Geologica Acta* **1**: 289–302.
- Moro, R., Bicudo, C., de Melo, M., and Schmitt, J. 2004. Paleoclimate of the late Pleistocene and Holocene at Lagoa Dourada, Parana State, southern Brazil. *Quaternary International* **114**: 87–99.
- Neukom, R., Luterbacher, J., Villalba, R., Kuttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.-C., Black, D.E., Christie, D.A., D'Arrigo, R., Lara, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urritia, R., and von Gunten, L. 2011. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* **37**: 35–51.
- Panario, D. and Gutierrez, O. 1999. The continental Uruguayan Cenozoic: and overview. *Quaternary International* **62**: 75–84.
- Piovano, E.L., Ariztegui, D., Cordoba, F., Coccale, M., and Sylvestre, F. 2009. Hydrological variability in South America below the Tropico of Capricorno (Pampas and Patagonia, Argentina) during the last 13.0 ka. In: Vimeux, F., Sylvestre, F., and Khodri, M. (Eds.) *Past Climate Variability from the Last Glacial Maximum to the Holocene in South America and Surrounding Regions*. Developments in Paleoenviromental Research Series (DPER), Springer, New York, New York, USA, pp. 323–351.
- Prevosti, F.J., Bonomo, M., and Tonni, E.P. 2004. La distribucion de Chrysocyon brachyurus (Illiger, 1811) (mammalia: carnivore: canidae) durante el Holoceno en la Argentina; Implicancias paleoambientales. *Mastozoologia neotropical* **11**: 27–43.
- Prieto, A.R. 1996. Late Quaternary vegetational and climate change in the Pampa Grassland of Argentina. *Quaternary Research* **54**: 73–88.
- Prieto, A.R. 2000. Vegetational history of the Late Glacial-Holocene transition in the grasslands of Eastern Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* **157**: 167–188.
- Prieto, A.R., Blasi, A., De Francesco, C., and Fernandez, C. 2004. Environmental history since 11,000 14C yr B.P. of the northeastern Pampas, Argentina, from alluvial sequences of the Lujan River. *Quaternary Research* **62**: 146–161.
- Quattrocchio, M.E., Borromei, A.M., Deschamps, C.M., Grill, S.C., and Zavala, C.A. 2008. Landscape evolution and climate changes in the Late Pleistocene-Holocene, southern Pampa (Argentina): evidence from palynology, mammals and sedimentology. *Quaternary International* **181**: 123–138.
- Roberts, N. 2009. Holocene climates. In: Gornitz, V. (Ed.). *Encyclopedia of Paleoclimatology and Ancient Environments*. Springer, New York, New York, USA, pp. 438–441.
- Tonni, E.P., Cione, A.L., and Figini, A.J. 1999. Predominance of arid climates indicated by mammals in the pampas of Argentina during the Late Pleistocene and Holocene. *Palaeogeography, Palaeoclimatology, Palaeoecology* **147**: 257–281.
- Zarate, M., Kemp, R.A., Espinosa, M., and Ferrero, L. 2000. Pedosedimentary and palaeoenvironmental

significance of a Holocene alluvial sequence in the southern Pampas, Argentina. *The Holocene* **10**: 481–488.

4.3 Predicted vs. Observed Global Warming Effects on ENSO

Computer model simulations have given rise to three claims regarding the influence of global warming on ENSO events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions (see, for example, Timmermann *et al.*, 1999; Collins 2000a,b; Cubasch *et al.*, 2001). However, as outlined in the following two subsections, this is generally not what observational data show. The data for nearly all historical records show frequent and strong El Niño activity increases during periods of colder temperatures (e.g., the Little Ice Age) and decreases during warm ones (e.g., Medieval Warm Period, Current Warm Period).

References

Collins, M. 2000a. Understanding uncertainties in the response of ENSO to greenhouse warming. *Geophysical Research Letters* **27**: 3509–3513.

Collins, M. 2000b. The El Niño Southern Oscillation in the second Hadley center coupled model and its response to greenhouse warming. *Journal of Climate* **13**: 1299–1312.

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S., and Yap, K.S. 2001. Projections of future climate change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P., Dai, X., Maskell, K., and Johnson, C.I. (Eds.) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the 3rd Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp. 525–582.

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M., and Roeckner, E. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature* **398**: 694–696.

4.3.1 Frequency and Intensity

Mendelssohn *et al.* (2005) performed a statistical analysis known as state-space decomposition on three El Niño-related indices (Southern Oscillation Index, its component sea level pressure series, and the NINO3 index) for the twentieth century. The stochastic cycles produced by the state-space models

were all relatively stationary, which, in the words of the investigative scientists, does “not support the idea that El Niños have become more frequent.” As to the magnitude of ENSO events, they say there were some “outlier events” in the later portion of the record, which may suggest ENSO magnitudes have increased in recent years, but they conclude “it is premature to tell.”

Lee and McPhaden (2010) used satellite observations of sea surface temperature (SST) in the past three decades “to examine SST in the CP region, distinguishing between the increases in El Niño intensity and changes in background SST.” The two U.S. researchers discovered the SSTs in the CP region during El Niño years are “getting significantly higher while those during La Niña and neutral years are not.” Therefore, they reason, “the increasing intensity of El Niño events in the CP region is not simply the result of the well-documented background warming trend in the western-Pacific warm pool,” but instead “it is the increasing amplitude of El Niño events that causes a net warming trend of SST in the CP region.”

Lee and McPhaden conclude their results “suggest that, at least for the past three decades, the warming of the warm pool in the CP region is primarily because of more intense El Niño events in that region.” In addition, they report, “in contrast to the CP region, the intensity of El Niño events in the EP region does not have a warming trend, and even has a cooling trend (though not significant at the 90% level of confidence) over the three-decade period.” They write, “further investigation is therefore needed to understand these issues better, given the uncertainty surrounding causal mechanisms and the implications the observed changes have for global climate and societal impacts.”

Noting DelSole and Tippet (2009) had recently demonstrated relatively short meteorological records, on the order of 50 years or less, “are not sufficient to detect trends in a mode of variability such as ENSO,” Ray and Giese (2012) explored the postulated global warming-ENSO connection by comparing sea surface temperatures (SSTs) derived from an ocean reanalysis with three widely used SST reconstructions. They used the reanalysis data to evaluate potential changes in ENSO characteristics over the period 1871–2008. The two researchers conclude, “there is no evidence that there are changes in the [1] strength, [2] frequency, [3] duration, [4] location or [5] direction of propagation of El Niño and La Niña anomalies caused by global warming during the period from 1871 to 2008.”

Observations: Temperature Records

Yeh *et al.* (2011) state there is an “expectation that ENSO [El Niño-Southern Oscillation] statistics would change under global warming, although the details remain uncertain because of the large spread of model projections for the 21st century (Guilyardi *et al.*, 2009).” In addition, they note there is evidence of “increasing intensity as well as occurrence frequency of the so-called Central Pacific (CP) El Niño events since the 1990s.” This brings up the question of whether the latter is a consequence of global warming.

In exploring this highly unsettled (Collins *et al.*, 2010) situation, Yeh *et al.* ran a multi-millennial CGCM (coupled general circulation model) simulation “to assess whether the natural changes in the frequency of CP El Niño occurrence simulated by the model are comparable to the observed changes over the last few decades,” suggesting, “if the changes are similar then we cannot rule out the possibility that the recent changes are simply natural variability.”

The five researchers report their control simulation—run for 4,200 years of data with the present values of greenhouse gases—“exhibits large variations of the occurrence frequency of the CP El Niño versus the eastern Pacific (EP) El Niño” and “simulates to some extent changes in the occurrence ratio of CP and EP El Niño in comparison with the observations.” Therefore, they conclude, “we cannot exclude the possibility that an increasing of occurrence frequency of CP El Niño during recent decades in the observation could be a part of natural variability in the tropical climate system,” providing more evidence for the likely cyclical origin of recent global warming.

Nicholls (2008) notes there has been a “long-running debate as to how the El Niño-Southern Oscillation (ENSO) might react to global warming,” and “the focus in most model studies on ENSO and climate change has been on whether the Pacific will tend to a more permanent El Niño state as the world warms due to an enhanced greenhouse effect.” Nicholls examined “trends in the seasonal and temporal behaviour of ENSO, specifically its phase-locking to the annual cycle over the past 50 years,” where phase-locking “means that El Niño and La Niña events tend to start about April–May and reach a maximum amplitude about December–February,” which is why he examined trends in ENSO indices for each month of the year.

The Australian researcher thus determined “there has been no substantial modulation of the

temporal/seasonal behaviour of the El Niño-Southern Oscillation”—as measured by the sea surface temperature averaged across the region 5°S–5°N by 120°W–170°W, and the Southern Oscillation Index (the non-standardized difference between sea level pressures at Tahiti and Darwin)—over the past 50 years, during what he describes as “a period of substantial growth in the atmospheric concentrations of greenhouse gases and of global warming.” Nicholls reports “the temporal/seasonal nature of the El Niño-Southern Oscillation has been remarkably consistent through a period of strong global warming,” clearly repudiating climate-model-derived inferences of global warming increasing both the frequency and intensity of ENSO events.

In a paper addressing “the need for a reliable ENSO index that allows for the historical definition of ENSO events in the instrumental record back to 1871,” Wolter and Timlin (2011) state their Multivariate ENSO Index (MEI) was originally defined by them (Wolter and Timlin, 1993, 1998) as “the first seasonally varying principal component of six atmosphere-ocean variable fields in the tropical Pacific basin.” This index, they note, “provides for a more complete and flexible description of the ENSO phenomenon than single variable ENSO indices.”

To improve even further on their earlier refinement, the two U.S. researchers describe their efforts “to boil the MEI concept down to its most essential components (based on sea level pressure and sea surface temperature) to enable historical analyses that more than double its period of record.” Their efforts, they note, were “designed to help with the assessment of ENSO conditions through as long a record as possible to be able to differentiate between ‘natural’ ENSO behavior in all its rich facets, and the ‘Brave New World’ of this phenomenon under evolving greenhouse gas-related climate conditions.”

Wolter and Timlin report, “the new MEI.ext confirms that ENSO activity went through a lull in the early- to mid-20th century, but was just about as prevalent one century ago as in recent decades.” They write, “so far, none of the behavior of recent ENSO events appears unprecedented, including duration, onset timing, and spacing in the last few decades compared to a full century before then.”

Evans *et al.* (2002) reconstructed gridded Pacific Ocean sea surface temperatures from coral stable isotope ($\delta^{18}\text{O}$) data, from which they assessed ENSO activity over the period 1607–1990. The results of their analysis show a period of relatively vigorous ENSO activity over the colder-than-present period of

1820–1860 was “similar to [that] observed in the past two decades.” Similarly, in a study partly based on the instrumental temperature record for the period 1876–1996, Allan and D’Arrigo (1999) found four persistent El Niño sequences similar to that of the 1990s, and using tree-ring proxy data covering the period 1706 to 1977, they found several other ENSO events of prolonged duration. There were four or five persistent El Niño sequences in each of the eighteenth and nineteenth centuries, and both these centuries were significantly colder than the final two decades of the twentieth century. This led them to conclude there is “no evidence for an enhanced greenhouse influence in the frequency or duration of ‘persistent’ ENSO event sequences.”

Brook *et al.* (1999) analyzed the layering of couplets of inclusion-rich calcite over inclusion-free calcite, and darker aragonite over clear aragonite, in two stalagmites from Anjohibe Cave in Madagascar, comparing their results with historical records of El Niño events and proxy records of El Niño events and sea surface temperatures derived from ice core and coral data. The cave-derived record of El Niño events compared well with the historical and proxy ice core and coral records, and these data indicated, Brook *et al.* report, “the period 1700–50 possibly witnessed the highest frequency of El Niño events in the last four and a half centuries while the period 1780–1930 was the longest period of consistently high El Niño occurrences.” Both of these periods were considerably cooler than the 1980s and 1990s.

Braganza *et al.* (2009) developed an annually resolved Pacific-basin-wide ENSO index for the period AD 1525–1982 based on tree-ring, coral, and ice-core data obtained from the western equatorial Pacific, New Zealand, the central Pacific, and subtropical North America—which constitute, they write, “a set of multiproxy indicators from locations that span a broader area of the Pacific basin than has been attempted previously.” According to the five researchers, “the proxy ENSO index over the last 450 years shows considerable amplitude and frequency modulation in the 3–10 year band on multidecadal time scales.” They further state, “in the context of the entire record, we find no pronounced signal of twentieth century climate change in ENSO variability.”

Meyerson *et al.* (2003) analyzed an annually dated ice core from the South Pole for the period 1487–1992, focusing on the marine biogenic sulfur species methanesulfonate (MS). They used orthogonal function analysis to calibrate the high-

resolution MS series with associated environmental series for the period of overlap (1973–1992). This procedure allowed them to derive a five-century history of ENSO activity and southeastern Pacific sea-ice extent; the latter parameter “is indicative of regional temperatures within the Little Ice Age period in the southeastern Pacific sea-ice sector.”

Meyerson *et al.* found a shift toward generally cooler conditions at about 1800 AD. This shift was concurrent with an increase in the frequency of El Niño events in the ice core proxy record, which contradicts what climate models generally predict. Their findings are, by contrast, harmonious with the historical El Niño chronologies of both South America (Quinn and Neal, 1992) and the Nile region (Quinn, 1992; Diaz and Pulwarty, 1994). These records depict, they note, “increased El Niño activity during the period of the Little Ice Age (nominally 1400–1900) and decreased El Niño activity during the Medieval Warm Period (nominally 950–1250),” as per Anderson (1992) and de Putter *et al.* (1998).

Wang *et al.* (2004) evaluated all ENSO events they could identify in existing records of the past 500 years to see if there was any significant increase in their frequency of their occurrence over the twentieth century. Although Wang *et al.* note El Niño frequency was a little higher in the twentieth century, and La Niña frequency was somewhat higher during the Little Ice Age, they report “ENSO frequency [was] relatively stationary during the last 500 years, including the Little Ice Age (1550–1850) and Modern Warming Period (the 20th century).” They note Diaz and Pulwarty (1994) found “the frequency of ENSO during the Little Ice Age does not differ greatly from that found in the 20th century based on singular spectrum analysis and evolutive spectral analysis.”

Herweijer *et al.* (2007) put into longer perspective “the famous droughts of the instrumental record (i.e., the 1930s Dust Bowl and the 1950s Southwest droughts),” using Palmer Drought Severity Index data found in the North American Drought Atlas prepared by Cook and Krusic (2004), which were derived from a network of drought-sensitive tree-ring chronologies (some stretching back to AD 800 and encompassing the Medieval Warm Period). The authors found “medieval megadroughts were forced by protracted La Niña-like tropical Pacific sea surface temperatures.” In addition, the data identify “a global hydroclimatic ‘footprint’ of the medieval era revealed by existing paleoclimatic archives from the tropical Pacific and ENSO-sensitive tropical and extratropical land regions.” The authors state, “this global pattern

Observations: Temperature Records

matches that observed for modern-day persistent North American drought,” namely, “a La Niña-like tropical Pacific.”

Khider *et al.* (2011) developed a history of ENSO variability over a period of time that included both the Medieval Climate Anomaly (MCA, AD 800–1300) and the Little Ice Age (LIA, AD 1500–1850) “by comparing the spread and symmetry of $\delta^{18}\text{O}$ values of individual specimens of the thermocline-dwelling planktonic foraminifer *Pulleniatina obliquiloculata* extracted from discrete time horizons of a sediment core collected in the Sulawesi Sea, at the edge of the western tropical Pacific warm pool,” and by interpreting the spread of individual $\delta^{18}\text{O}$ values “to be a measure of the strength of both phases of ENSO.” The five researchers used the symmetry of the $\delta^{18}\text{O}$ distributions “to evaluate the relative strength/frequency of El Niño and La Niña events.” They report “the strength/frequency of ENSO, as inferred from the spread of the $\delta^{18}\text{O}$ distributions, during the MCA and during the LIA was not statistically distinguishable and was comparable to that of the 20th century.” They write, their results suggest “ENSO during the MCA was skewed toward stronger/more frequent La Niña than El Niño,” an observation they note is “consistent with the medieval megadroughts documented from sites in western North America.”

Cobb *et al.* (2003) generated multi-century, monthly-resolved records of tropical Pacific climate variability over the last millennium by splicing together overlapping fossil-coral records from the central tropical Pacific. This allowed them “to characterize the range of natural variability in the tropical Pacific climate system with unprecedented fidelity and detail.” They discovered “ENSO activity in the seventeenth-century sequence [was] not only stronger, but more frequent than ENSO activity in the late twentieth century.” They also found “there [were] 30-yr intervals during both the twelfth and fourteenth centuries when ENSO activity [was] greatly reduced relative to twentieth-century observations.” Once again, ENSO activity is shown to have been much greater and more intense during the cold of the Little Ice Age than the warmth of the late twentieth century.

Eltahir and Wang (1999) used water-level records of the Nile River as a proxy for El Niño episodes over the past 14 centuries. Although the frequency of El Niño events over the 1980s and 1990s was high, they found it was not without precedent, being similar to values observed near the start of the twentieth century and much the same as those “experienced during the

last three centuries of the first millennium.” The latter period, according to Esper *et al.* (2002), was also significantly cooler than the latter part of the twentieth century.

Langton *et al.* (2008) used geochemical data obtained by analysis of a sediment core extracted from the shallow-silled and intermittently dysoxic Kau Bay in Halmahera, Indonesia (1°N, 127.5°E) to reconstruct century-scale climate variability within the Western Pacific Warm Pool over the past 3,500 years. Langton *et al.* report, “basin stagnation, signaling less El Niño-like conditions, occurred during the time frame of the Medieval Warm Period (MWP), from ca. 1000 to 750 years BP,” which was “followed by an increase in El Niño activity that culminated at the beginning of the Little Ice Age ca. 700 years BP.” Thereafter, their record suggests, “the remainder of the Little Ice Age was characterized by a steady decrease in El Niño activity with warming and freshening of the surface water that continued to the present.” In addition, they state, “the chronology of flood deposits in Laguna Pallcacocha, Ecuador (Moy *et al.*, 2002; Rodbell *et al.*, 1999), attributed to intense El Niño events, shows similar century-scale periods of increased [and decreased] El Niño frequency.”

The nine researchers conclude “the finding of similar century-scale variability in climate archives from two El Niño-sensitive regions on opposite sides of the tropical Pacific strongly suggests they are dominated by the low-frequency variability of ENSO-related changes in the mean state of the surface ocean in [the] equatorial Pacific,” and the “century-scale variability,” as they describe it, suggests global warming typically tends to retard El Niño activity and global cooling tends to promote it.

Woodroffe *et al.* (2003) confirmed this finding applied over an even longer period of time. Using oxygen isotope ratios obtained from *Porites* microatolls at Christmas Island in the central Pacific to provide high-resolution proxy records of ENSO variability since 3.8 thousand years ago (ka), they found, “individual ENSO events in the late Holocene [3.8–2.8 ka] appear at least as intense as those experienced in the past two decades.” In addition, “geoarcheological evidence from South America (Sandweiss *et al.*, 1996), Ecuadorian varved lake sediments (Rodbell *et al.*, 1999), and corals from Papua New Guinea (Tudhope *et al.*, 2001) indicate that ENSO events were considerably weaker or absent between 8.8 and 5.8 ka,” the warmest period of the Holocene. They report, “faunal remains from archeological sites in Peru (Sandweiss *et al.*, 2001)

indicate that the onset of modern, rapid ENSO recurrence intervals was achieved only after ~4-3 ka,” or during the long cold interlude that preceded the Roman Warm Period (McDermott *et al.*, 2001).

Wei *et al.* (2007) reconstructed three mid-Holocene sea surface temperature (SST) records spanning more than 30 years using Sr/Ca ratios derived from cores of three *Porites lutea* colonies in the fringe reef at Dadonghai, Sanya in southern Hainan Island, which lived about 6,000 years ago at a water depth similar to that of modern coral at that location (approximately 18°12'N, 109°33'E). According to the six researchers, “the results indicate warmer than present climates between circa 6100 yr B.P. and circa 6500 yr B.P. with the mid-Holocene average minimum monthly winter SSTs, the average maximum monthly summer SSTs, and the average annual SSTs being about 0.5°–1.4°C, 0°–2.0°C, and 0.2°–1.5°C higher, respectively, than they were during 1970–1994.” In addition, they report, “ENSO variability in the mid-Holocene SSTs was weaker than that in the modern record, and the SST record with the highest summer temperatures from circa 6460 yr B.P. to 6496 yr B.P. shows no robust ENSO cycle.”

McGregor and Gagan (2004) used several annually resolved fossil *Porites* coral $\delta^{18}\text{O}$ records to investigate the characteristics of ENSO events over a period of time in which Earth cooled substantially. For comparison, study of a modern coral core provided evidence of ENSO events for the period 1950–1997, the results of which analysis suggest they occurred at a rate of 19 events/century. The mid-Holocene coral $\delta^{18}\text{O}$ records, by contrast, showed reduced rates of ENSO occurrence: 12 events/century for the period 7.6–7.1 ka, eight events/century for the period 6.1–5.4 ka, and six events/century at 6.5 ka. For the period 2.5–1.7 ka, the results were quite different, with all of the coral records revealing “large and protracted $\delta^{18}\text{O}$ anomalies indicative of particularly severe El Niño events.” They note, for example, “the 2.5 ka Madang PNG coral records a protracted 4-year El Niño, like the 1991–1994 event, but almost twice the amplitude of [the] 1997–1998 event (Tudhope *et al.*, 2001).” In addition, “the 2 ka Muschu Island coral $\delta^{18}\text{O}$ record shows a severe 7-year El Niño, longer than any recorded Holocene or modern event.” And they add, “the 1.7 ka *Porites* microatoll of Woodroffe *et al.* (2003) also records an extreme El Niño that was twice the amplitude of the 1997–1998 event.” Taken together, these results portray a “mid-Holocene El Niño suppression and late

Holocene amplification.”

That there tend to be fewer and weaker ENSO events during warm periods is documented further by Riedinger *et al.* (2002). In a 7,000-year study of ENSO activity in the vicinity of the Galapagos Islands, they determined “mid-Holocene [7130 to 4600 yr BP] El Niño activity was infrequent,” when global air temperature was significantly warmer than it is now, but both the “frequency and intensity of events increased at about 3100 yr BP,” when the world cooled below today’s temperatures. Throughout the former 2,530-year warm period, there were only 23 strong to very strong El Niños and 56 moderate events, according to their data, whereas throughout the most recent (and significantly colder) 3,100-year period, they identified 80 strong to very strong El Niños and 186 moderate events. These numbers correspond to rates of 0.9 strong and 2.2 moderate occurrences per century in the earlier, warm period and 2.7 strong and 6.0 moderate occurrences per century in the latter, cool period, an approximate tripling of the rate of occurrence of both strong and moderate El Niños in going from the warmth of the Holocene “Climatic Optimum” to the colder conditions of the past three millennia.

Similar results have been reported by Andrus *et al.* (2002), who found sea surface temperatures off the coast of Peru were 3 to 4°C warmer 6,000 years ago than in the 1990s and provided little evidence of El Niño activity.

Moy *et al.* (2002) analyzed a sediment core from lake Laguna Pallcacocha in the southern Ecuadorian Andes, producing a proxy measure of ENSO over the past 12,000 years. For the moderate and strong ENSO events detected by their analytical techniques (weaker events are not registered), “the overall trend exhibited in the Pallcacocha record includes a low concentration of events in the early Holocene, followed by increasing occurrence after 7,000 cal. yr BP, with peak event frequency occurring at ~1,200 cal. yr BP,” after which the frequency of events declines dramatically to the present, they write.

In the last 1,200 years of this record, the decline in the frequency of ENSO events is anything but smooth. In coming out of the Dark Ages Cold Period, one of the coldest intervals of the Holocene (McDermott *et al.*, 2001), the number of ENSO events drops by an order of magnitude, from a high of approximately 33 events per 100 yr to a low of about three events per 100 yr, centered approximately on the year AD 1000, right in the middle of the Medieval Warm Period as delineated by the work of Esper *et al.*

Observations: Temperature Records

(2002). At approximately AD 1250, the frequency of ENSO events exhibits a new peak of approximately 27 events per century in the midst of the longest sustained cold period of the Little Ice Age, again as delineated by the work of Esper *et al.* Finally, ENSO event frequency declines in zigzag fashion to a low on the order of four to five events per century at the start of the Current Warm Period, which according to the temperature history of Esper *et al.* begins at about 1940.

A similar decline in ENSO events during the Medieval Warm Period is noted by Rein *et al.* (2004), who derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin on the edge of the Peruvian shelf about 80 km west of Lima, Peru. Rein *et al.* found a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the late Medieval period. They report “lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250.” They write, “all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly.”

In addition, they report, “this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain.” Rein *et al.* note, for example, “from an Ecuadorian lake record where moderate to strong El Niño floods are recorded (Moy *et al.*, 2002), a minimum of such events is reported during the upper Medieval period.” They also note the oldest (A.D. 928–961) of the five “time windows” on central Pacific El Niño activity provided by the corals investigated by Cobb *et al.* (2003) exhibits evidence for weaker El Niños than all subsequent time windows extending to 1998. In addition, they note, “extreme long-lasting droughts that peaked coincident with those in the Peru record around A.D. 1160, are reported from several archives in the western USA and Southern Patagonia (Stine, 1994),” and near-contemporaneous dry periods “also occurred in the tropical Andes (Abbot *et al.*, 1997; Binford *et al.*, 1997), Oman (Fleitmann *et al.*, 2003) and eastern Africa (De Putter *et al.*, 1998; Verschuren *et al.*, 2000).” They conclude, “hints that these droughts are not only coinciding events but related to El Niño anomalies come from the high-resolution Moon Lake (North Dakota, USA) salinity record (Laird *et al.*, 1996).”

Rittenour *et al.* (2000) studied a recently revised New England varve chronology derived from proglacial lakes formed during the recession of the Laurentide ice sheet some 17,500 to 13,500 years ago, finding “the chronology shows a distinct interannual band of enhanced variability suggestive of El Niño–Southern Oscillation (ENSO) teleconnections into North America during the late Pleistocene, when the Laurentide ice sheet was near its maximum extent ... during near-peak glacial conditions.” But during the middle of the Holocene, when it was considerably warmer, Overpeck and Webb (2000) report data from corals suggest “interannual ENSO variability, as we now know it, was substantially reduced, or perhaps even absent.”

Nederbragt and Thurnow (2005) analyzed the varve thickness profiles of two sediment cores retrieved from the Santa Barbara Basin off the coast of California, USA, to determine how the strength of the El Niño/Southern Oscillation (ENSO) phenomenon has varied there over the past 15,000 years. The records show the strength of the ENSO signal fluctuated on multidecadal to centennial timescales. In spite of this variability, Nederbragt and Thurnow note power spectra analysis gave no indication of a unidirectional trend in either the frequency or amplitude of ENSO events. The ENSO signal at millennial timescales was reported to be “more or less constant.”

In a follow-up to their 2004 work (Rein *et al.*, 2004), Rein *et al.* (2005) developed high-resolution marine proxy data for El Niño variability over the last 20,000 years, obtained by analyzing a sediment core retrieved from a sheltered basin on the edge of the Peruvian shelf (12°03'S, 77°39.8'W) about 80 km west of Lima. The most well-defined feature of the record was a dramatic depression of El Niño activity between about 5.6 and 8 thousand years ago, which coincided with the major warmth of the Holocene Climatic Optimum. The next-most significant feature was “the medieval period of low El Niño activity,” which the researchers describe as “the major anomaly during the late Holocene”—i.e., the Medieval Warm Period—as their data indicate “El Niños were persistently weak between 800 and 1250 AD.”

Studying the past millennium in more detail, Rein *et al.* found signs of just the opposite behavior, though on a much shorter timescale: On average, they note, “temperature reconstructions show higher temperatures with increased El Niño activity.” That finding was to be expected, however, for that is what El Niños do—they create significant spikes in mean

global air temperature, as was dramatically demonstrated by the 1997–1998 El Niño that produced the highest mean annual temperature (1998) of the entire satellite record and gave the record its slightly upward-trending slope. Although El Niños may significantly impact short-term climate, periodically nudging global temperatures upward, they in turn are even more strongly affected by long-term climate, as demonstrated by the findings discussed in the preceding paragraphs of this section, where it is readily seen long-term warmth depresses El Niño activity.

In providing some additional examples of this phenomenon—the overriding power of centennial- to millennial-scale climate variability compared to decadal to multidecadal variability (in terms of what drives what when it comes to changes in temperature and El Niño activity)—Rein *et al.* report, during the Medieval Warm Period, when “Northern Hemisphere temperatures peaked,” there was “extraordinarily weak El Niño activity”; in the late thirteenth and early seventeenth centuries, “temperatures in the Northern Hemisphere were rather cool but El Niño activity was high”; and during the nineteenth century, when the Northern Hemisphere began to warm as the planet commenced its recovery from the global chill of the Little Ice Age, El Niño activity began to decline, as Medieval-Warm-Period-like conditions were once again being established as the Current Warm Period was coming into existence.

In light of these observations, it is quite likely the slight global warming evident in the satellite record of the past three decades was simply a natural consequence of El Niño activity, which will likely subside somewhat as the Current Warm Period (which we contend to be primarily a product of Earth’s natural millennial-scale oscillation of climate) becomes more firmly entrenched at a slightly higher temperature commensurate with that of the Medieval Warm Period.

Another explanation may rest in the work of Verdon and Franks (2006), who used “proxy climate records derived from paleoclimate data to investigate the long-term behavior of the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO)” over the past 400 years. The pair of researchers found climate shifts associated with changes in the PDO “occurred with a similar frequency to those documented in the 20th century.” In addition, and more importantly, they find “phase changes in the PDO have a propensity to coincide with changes in the relative frequency of ENSO

events, where the positive phase of the PDO is associated with an enhanced frequency of El Niño events, while the negative phase is shown to be more favourable for the development of La Niña events.”

The two Australian scientists note the numerous El Niño events of the recent past “have been reported as unusual, and have even been suggested to be possible evidence of anthropogenic climate change [e.g., Trenberth and Hoar, 1996].” However, they continue, “the paleo records suggest that the apparent lack of La Niña events and high frequency of El Niño events over the past two decades may not be abnormal and could be attributed to the fact that during this time the PDO has been in a positive phase,” such that “when the PDO switches back to a negatively dominated phase, it is quite likely that the frequency of La Niña events will increase once again.” Consequently, there is no compelling reason to conclude the recent preponderance of El Niño events over La Niña events is a “fingerprint” of CO₂-induced global warming, especially in light of the evidence highlighted in this section.

Davies *et al.* (2012) note, “variations in the frequency and amplitude of the El Niño-Southern Oscillation (ENSO) recorded in both instrumental and paleoclimate archives have led to speculation that global warming may cause fundamental changes in this preeminent mode of global interannual climate variability (Fedorov and Philander, 2000).” They note there is speculation “warmer climates may promote a permanent El Niño state (Wara *et al.*, 2005; Fedorov *et al.*, 2006).” In a study designed to explore this possibility further, Davies *et al.* analyzed the latest Cretaceous laminated Marca Shale of California, which permits “a seasonal-scale reconstruction of water column flux events and, hence, interannual paleoclimate variability,” during what is known to have been a “past ‘greenhouse’ climate state.”

The four researchers report “significant spectral peaks obtained from lamina-derived time series analysis of the Marca Shale closely resemble those of modern and historical ENSO variability.” In addition, “the parameters from which the time series are derived (biogenic- and terrigenous-lamina thickness and bioturbation index) appear directly related to the marine production and flux, incursion of oxygenated waters, and input of terrigenous sediment that would be influenced by ENSO-type mechanisms of interannual variability.” Davies *et al.* say there is “little support for the existence of a ‘permanent El Niño’ in the Late Cretaceous, in the sense of the continual El Niño state depicted by Fedorov *et al.* (2006).” They

Observations: Temperature Records

say this evidence “builds on results from the Cretaceous Arctic (Davies *et al.*, 2011) and from younger Eocene and Miocene warm periods (Huber and Caballero, 2003; Galeotti *et al.*, 2010; Lenz *et al.*, 2010) to emphasize that there was robust ENSO variability in past ‘greenhouse’ episodes and that future warming will be unlikely to promote a permanent El Niño state.”

References

- Abbot, M.B., Binford, M.W., Brenner, M., and Kelts, K.R. 1997. A 3500 C¹⁴ yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* **47**: 169–180.
- Allan, R.J. and D’Arrigo, R.D. 1999. “Persistent” ENSO sequences: how unusual was the 1990-1995 El Niño? *The Holocene* **9**: 101–118.
- Anderson, R.Y. 1992. Long-term changes in the frequency of occurrence of El Niño events. In: Diaz, H.F. and Markgraf, V. (Eds.) *El Niño. Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, Cambridge, UK, pp. 193–200.
- Andrus, C.F.T., Crowe, D.E., Sandweiss, D.H., Reitz, E.J., and Romanek, C.S. 2002. Otolith $\delta^{18}\text{O}$ record of mid-Holocene sea surface temperatures in Peru. *Science* **295**: 1508–1511.
- Binford, M.A., Kolata, M., Brenner, M., Janusek, L., Seddon, M., Abbott, M., and Curtis, J. 1997. Climate variation and the rise and fall of an Andean civilization. *Quaternary Research* **47**: 235–248.
- Braganza, K., Gergis, J.L., Power, S.B., Risbey, J.S., and Fowler, A.M. 2009. A multiproxy index of the El Niño-Southern Oscillation, A.D. 1525–1982. *Journal of Geophysical Research* **114**: 10.1029/2008JD010896.
- Brook, G.A., Rafter, M.A., Railsback, L.B., Sheen, S.-W., and Lundberg, J. 1999. A high-resolution proxy record of rainfall and ENSO since AD 1550 from layering in stalagmites from Anjohibe Cave, Madagascar. *The Holocene* **9**: 695–705.
- Cobb, K.M., Charles, C.D., Cheng, H., and Edwards, R.L. 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* **424**: 271–276.
- Collins, M., An, S.-I., Cai, W., Ganachaud, A., Guilyardi, E., Jin, F.-F., Jochum, M., Lengaigne, M., Power, S., Timmermann, A., Vecchi, G., and Wittenberg, A. 2010. The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience* **3**: 391–397.
- Cook, E.R. and Krusic, P.J. 2004. *North American Summer PDSI Reconstructions*. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series No. 2004-045, NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, USA.
- Davies, A., Kemp, A.E.S., and Palike, H. 2011. Tropical ocean-atmosphere controls on inter-annual climate variability in the Cretaceous Arctic. *Geophysical Research Letters* **38**: 10.1029/2010GL046151.
- Davies, A., Kemp, A.E.S., Weedon, G.P., and Barron, J.A. 2012. El Niño-Southern Oscillation variability from the Late Cretaceous Maraca Shale of California. *Geology* **40**: 15–18.
- DelSole, T. and Tippett, M.K. 2009. Average predictability time. Part I: Theory. *Journal of the Atmospheric Sciences* **66**: 1172–1187.
- de Putter, T., Loutre, M.-F., and Wansard, G. 1998. Decadal periodicities of Nile River historical discharge (A.D. 622–1470) and climatic implications. *Geophysical Research Letters* **25**: 3195–3197.
- Diaz, H.F. and Pulwarty, R.S. 1994. An analysis of the time scales of variability in centuries-long ENSO-sensitive records of the last 1000 years. *Climatic Change* **26**: 317–342.
- Eltahir, E.A.B. and Wang, G. 1999. Nilometers, El Niño, and climate variability. *Geophysical Research Letters* **26**: 489–492.
- Esper, J., Cook, E.R., and Schweingruber, F.H. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.
- Evans, M.N., Kaplan, A., and Cane, M.A. 2002. Pacific sea surface temperature field reconstruction from coral $\delta^{18}\text{O}$ data using reduced space objective analysis. *Paleoceanography* **17**: U71–U83.
- Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., deMenocal, P.B., Barreiro, M., Pacanowski, R.C., and Philander, S.G. 2006. The Pliocene paradox (mechanisms for a permanent El Niño). *Science* **312**: 1485–1489.
- Fedorov, A.V. and Philander, S.G. 2000. Is El Niño changing? *Science* **288**: 1997–2002.
- Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter, A. 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* **300**: 1737–1739.
- Galeotti, S., von der Heydt, A., Huber, M., Bice, D., Dijkstra, H., Jilbert, T., Lanci, L., and Reichert, G.J. 2010. Evidence for active El Niño Southern Oscillation variability in the Late Miocene greenhouse climate. *Geology* **38**: 419–421.
- Guilyardi, E., Wittenberg, A., Fedorov, A., Collins, M.,

Climate Change Reconsidered II

- Wang, C., Capotondi, A., Jan, G., Oldenborgh, V., and Stockdale, T. 2009. Understanding El Niño in ocean-atmosphere general circulation models: progress and challenges. *Bulletin of the American Meteorological Society* **90**: 325–340.
- Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.
- Huber, M. and Caballero, R. 2003. Eocene El Niño: evidence for robust tropical dynamics in the “hothouse.” *Science* **299**: 877–881.
- Khider, D., Stott, L.D., Emile-Geay, J., Thunell, R., and Hammond, D.E. 2011. Assessing El Niño Southern Oscillation variability during the past millennium. *Paleoceanography* **26**: 10.1029/2011PA002139.
- Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F. 1996. Greater drought intensity and frequency before AD 1200 in the northern Great Plains, USA. *Nature* **384**: 552–554.
- Langton, S.J., Linsley, B.K., Robinson, R.S., Rosenthal, Y., Oppo, D.W., Eglinton, T.I., Howe, S.S., Djajadihardja, Y.S., and Syamsudin, F. 2008. 3500 yr record of centennial-scale climate variability from the Western Pacific Warm Pool. *Geology* **36**: 795–798.
- Lee, T. and McPhaden, M.J. 2010. Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters* **37**: 10.1029/2010GL044007.
- Lenz, O.K., Wilde, V., Riegel, W., and Harms, F.J. 2010. A 600 k.y. record of El Niño-Southern Oscillation (ENSO): evidence for persisting teleconnections during the Middle Eocene greenhouse climate of Central Europe. *Geology* **38**: 627–630.
- Magillian, F.J. and Goldstein, P.S. 2001. El Niño floods and culture change: A late Holocene flood history for the Rio Moquegua, southern Peru. *Geology* **29**: 431–434.
- McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.
- McGregor, H.V. and Gagan, M.K. 2004. Western Pacific coral $\delta^{18}\text{O}$ records of anomalous Holocene variability in the El Niño-Southern Oscillation. *Geophysical Research Letters* **31**: 10.1029/2004GL019972.
- Mendelssohn, R., Bograd, S.J., Schwing, F.B., and Palacios, D.M. 2005. Teaching old indices new tricks: a state-space analysis of El Niño related climate indices. *Geophysical Research Letters* **32**: L07709, doi:10.1029/2005GL022350.
- Meyerson, E.A., Mayewski, P.A., Kreutz, K.J., Meeker, D., Whitlow, S.I., and Twickler, M.S. 2003. The polar expression of ENSO and sea-ice variability as recorded in a South Pole ice core. *Annals of Glaciology* **35**: 430–436.
- Moy, C.M., Seltzer, G.O., Rodbell, D.T., and Anderson D.M. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* **420**: 162–165.
- Nederbragt, A.J. and Thurow, J. 2005. Amplitude of ENSO cycles in the Santa Barbara Basin, off California, during the past 15,000 years. *Journal of Quaternary Science* **20**: 447–456.
- Nicholls, N. 2008. Recent trends in the seasonal and temporal behaviour of the El Niño-Southern Oscillation. *Geophysical Research Letters* **35**: 10.1029/2008GL034499.
- Overpeck, J. and Webb, R. 2000. Nonglacial rapid climate events: past and future. *Proceedings of the National Academy of Sciences USA* **97**: 1335–1338.
- Quinn, W.H. 1992. A study of Southern Oscillation-related climatic activity for A.D. 622–1990 incorporating Nile River flood data. In: Diaz, H.F. and Markgraf, V. (Eds.) *El Niño. Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, Cambridge, UK, pp. 119–149.
- Quinn, W.H. and Neal, V.T. 1992. The historical record of El Niño events. In: Bradley, R.S. and Jones, P.D. (Eds.) *Climate Since A.D. 1500*. Routledge, London, UK, pp. 623–648.
- Ray, S. and Giese, B.S. 2012. Historical changes in El Niño and La Niña characteristics in an ocean reanalysis. *Journal of Geophysical Research* **117**: 10.1029/2012JC008031.
- Rein, B., Luckge, A., Reinhardt, L., Sirocko, F., Wolf, A., and Dullo, W.-C. 2005. El Niño variability off Peru during the last 20,000 years. *Paleoceanography* **20**: 10.1029/2004PA001099.
- Rein B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.
- Riedinger, M.A., Steinitz-Kannan, M., Last, W.M., and Brenner, M. 2002. A ~6100 ^{14}C yr record of El Niño activity from the Galapagos Islands. *Journal of Paleolimnology* **27**: 1–7.
- Rittenour, T.M., Brigham-Grette, J., and Mann, M.E. 2000. El Niño-like climate teleconnections in New England during the late Pleistocene. *Science* **288**: 1039–1042.
- Rodbell, D.T., Seltzer, G.O., Anderson, D.M., Abbott, M.B., Enfield, D.B., and Newman, J.H. 1999. An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. *Science* **283**: 516–520.

Observations: Temperature Records

Sandweiss, D.H., Richardson III, J.B., Reitz, E.J., Rollins, H.B., and Maasch, K.A. 1996. Geoarchaeological evidence from Peru for a 5000 years BP onset of El Niño. *Science* **273**: 1531–1533.

Sandweiss, D.H., Maasch, K.A., Burger, R.L., Richardson III, J.B., Rollins, H.B., and Clement, A. 2001. Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru. *Geology* **29**: 603–606.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.

Trenberth, K.E. and Hoar, T.J. 1996. The 1990–1995 El Niño–Southern Oscillation event: longest on record. *Geophysical Research Letters* **23**: 57–60.

Tudhope, A.W., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M., and Shimmield, G.B. 2001. Variability in the El Niño–Southern Oscillation through a glacial-interglacial cycle. *Science* **291**: 1511–1517.

Verdon, D.C. and Franks, S.W. 2006. Long-term behaviour of ENSO: interactions with the PDO over the past 400 years inferred from paleoclimate records. *Geophysical Research Letters* **33**: 10.1029/2005GL025052.

Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

Wang, S., Zhu, J., Cai, J.m and Wen, X. 2004. Reconstruction and analysis of time series of ENSO for the last 500 years. *Progress in Natural Science* **14**: 1074–1079.

Wara, M.W., Ravelo, A.C., and Delaney, M.L. 2005. Permanent El Niño-like conditions during the Pliocene warm period. *Science* **309**: 758–761.

Wei, G., Deng, W., Yu, K., Li, X.-H., Sun, W., and Zhao, J.-X. 2007. Sea surface temperature records in the northern South China Sea from mid-Holocene coral Sr/Ca ratios. *Paleoceanography* **22**: 10.1029/2006PA001270.

Wells, L.E. 1990. Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru. *Geology* **18**: 1134–1137.

Wolter, K. and Timlin, M.S. 1993. Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proceedings of the 17th Climate Diagnostics Workshop, Norman, Oklahoma. NOAA/NMC/CAC, NSSL, Oklahoma Climate Survey, CIMMS and the School of Meteorology, University of Oklahoma, Norman, Oklahoma, USA, pp. 52–57.

Wolter, K. and Timlin, M.S. 1998. Measuring the strength of ENSO events—how does 1997/98 rank? *Weather* **53**: 315–324.

Wolter, K. and Timlin, M.S. 2011. El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *International Journal of Climatology* **31**: 1074–1087.

Woodroffe, C.D., Beech, M.R., and Gagan, M.K. 2003. Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls. *Geophysical Research Letters* **30**: 10.1029/2002GL015868.

Yeh, S.-W., Kirtman, B.P., Kug, J.-S., Park, W., and Latif, M. 2011. Natural variability of the central Pacific El Niño event on multi-centennial timescales. *Geophysical Research Letters* **38**: 10.1029/2010GL045886.

4.3.2 Influence on Extreme Weather Events

Computer model simulations have given rise to concerns that weather-related disasters will be exacerbated under warm, El Niño conditions. The validity of this assertion is challenged by the studies reported in this section, which demonstrate ENSO events generally do not lead to greater frequency or severity of extreme weather events.

Changnon (1999) determined adverse weather events attributed to the El Niño of 1997–1998 cost the United States economy \$4.5 billion and contributed to the loss of 189 lives, which is serious indeed. On the other hand, he determined El Niño-related benefits amounted to approximately \$19.5 billion—resulting primarily from reduced energy costs, industry sales, and reduction in hurricane damage—and a total of 850 lives were saved, thanks to the reduction of bad winter weather. Thus the net impact of the 1997–1998 El Niño on the United States, Changnon writes, was “surprisingly positive,” in stark contrast to what was often reported in the media and by climate alarmists, who tended, in his words, “to focus only on the negative outcomes.”

Another “surprisingly positive” consequence of El Niños is their tendency to moderate the frequency and intensity of Atlantic hurricanes. Working with data for 1950–1998, Wilson (1999) determined the probability of having three or more intense hurricanes during a warmer El Niño year was approximately 14 percent, and during a cooler non-El Niño year the probability jumped to 53 percent. Similarly, in a study of tropical storm and hurricane strikes along the southeast coast of the United States over the entire last century, Muller and Stone (2001) determined “more tropical storm and hurricane events can be anticipated during La Niña seasons [3.3 per season] and fewer during El Niño seasons [1.7 per season].”

In another study of Atlantic basin hurricanes, this

one considering the period 1925 to 1997, Pielke and Landsea (1999) report average hurricane wind speeds during warmer El Niño years were about six meters per second lower than during cooler La Niña years. In addition, they report hurricane damage during cooler La Niña years was twice as great as during warmer El Niño years. These year-to-year variations indicate hurricane frequency and intensity—as well as damage—tend to decline under warmer El Niño conditions, just the opposite of the impression typically conveyed to the public.

In the North Indian Ocean, Singh *et al.* (2000) studied tropical cyclone data pertaining to the period 1877–1998, finding tropical cyclone frequency declined there during the months of most severe cyclone formation (November and May), when ENSO was in a warm phase. Similarly, De Lange and Gibb (2000) studied New Zealand storm surges recorded by several tide gauges in Tauranga Harbor over the period 1960–1998, finding a considerable decline in both the annual number of such events and their magnitude in the latter (warmer) half of the nearly four-decade record, noting La Niña seasons typically experienced more storm surge days than El Niño seasons. Regarding Australia, Kuhnelt and Coates (2000) found yearly fatality event-days due to floods, bushfires, and heatwaves in 1876–1991 were greater in cooler La Niña years than in warmer El Niño years.

In a study of breeding populations of Cory's Shearwaters on the Tremiti Islands of Italy, Bricchetti *et al.* (2000) found survival rates of the birds during El Niño years were greater than during La Niña years, which they attribute to the calming influence of El Niño on Atlantic hurricanes.

Elsner *et al.* (2001) used annual U.S. hurricane data obtained from the U.S. National Oceanic and Atmospheric Administration, plus data obtained from the Joint Institute for the Study of the Atmosphere and the Oceans for average sea surface temperature (SST) anomalies for the region bounded by 6°N to 6°S latitude and 90°W to 180°W longitude (the “cold tongue index” or CTI) to discover whether there was a connection between the number of hurricanes that hit the eastern coast of the United States each year and the presence or absence of El Niño conditions. Based on data for the period 1901–2000, they found “when CTI values indicate below normal equatorial SSTs, the probability of a U.S. hurricane increases.” Or as they describe the relationship in another place, “the annual count of hurricanes is higher when values of the CTI are lower (La Niña events).” Thus the entire past century of real-world hurricane experience

indicates the yearly number of U.S. land-falling hurricanes has tended to decrease during El Niño conditions, as has the overall occurrence of hurricanes in the Atlantic basin.

Schwartz and Schmidlin (2002) examined past issues of *Storm Data*—a publication of the U.S. National Weather Service (NWS)—to compile a blizzard database for the years 1959–2000 for the conterminous United States. They analyzed the data to determine temporal trends and spatial patterns of U.S. blizzards, as well as their relationship to ENSO. Over the 41-year period of their study, they identified 438 blizzards, an average of 10.7 blizzards per year. Year-to-year blizzard variability was significant, however, with the number of annual blizzards ranging from a low of one in the winter of 1980–1981 to a high of 27 during the 1996–1997 winter. In addition, a weak but marginally significant relationship with ENSO was noted, with a tendency for two to three more blizzards to occur during La Niña winters than during El Niño winters.

Hudak and Young (2002) used an objective method of identifying June through November storms in the southern Beaufort Sea based on surface wind speed over the period 1970–1995, finding considerable year-to-year variation in the number of storms but no discernible trend. They also observed a small increase in the number of storms during El Niño vs. La Niña years, but they report “due to the relatively small number of cases, no statistical significance can be associated with this difference.” Thus, in a region of the world where climate models predict the effects of CO₂-induced global warming should be most evident, the past quarter-century has seen no change in the number of June–November storms.

Higgins *et al.* (2002) examined the influence of two important sources of Northern Hemispheric climate variability—ENSO and the Arctic Oscillation (AO)—on winter (Jan–Mar) daily temperature extremes throughout the conterminous United States over the 50-year period 1950–1999. This work revealed considerable decadal variability in surface air temperatures. Nevertheless, during El Niño years the number of extreme temperature days was found to decrease by around 10 percent, and during La Niña years they increased by around 5 percent. They found little or no difference in the number of extreme temperature days between the AO's positive and negative phases.

Goddard and Dilley (2005) state the huge reported “cost” of El Niño events “contributes greatly

Observations: Temperature Records

to misconceptions about the global climate effects and socioeconomic impacts of El Niño and La Niña.” They note the monetary figures typically bandied about represent a gross estimate of all hydro-meteorological impacts worldwide in specific El Niño years, but they note “how these losses compare with those during ENSO-neutral periods has not been established,” adding, “during El Niño events, El Niño is implicitly assumed to be associated with all climate-related losses.” They thus embarked on a study intended to provide the missing information.

Goddard and Dilley arrive at three major conclusions. First, they conclude “perturbation to precipitation over land areas is only weakly affected by ENSO extremes,” as they found “the risk of widespread extreme precipitation anomalies during ENSO extremes is comparable to that during neutral conditions” and “the highest values of integrated rainfall perturbation are not greater during ENSO extremes than during neutral conditions.” Second, they found “the frequency of reported climate-related disasters does not increase during El Niño/La Niña years relative to neutral years.” And third, they found seasonal rainfall forecast skill increases “in magnitude and coverage, during ENSO extremes,” such that “the prudent use of climate forecasts could mitigate adverse impacts and lead instead to increased beneficial impacts, which could transform years of ENSO extremes into the least costly to life and property.”

Among the beneficial impacts of ENSO extremes Goddard and Dilley say could yield a more complete appreciation of the differing socioeconomic impacts of El Niño and La Niña events is the well-established fact that “tropical Atlantic hurricanes that threaten the southeastern United States, the Caribbean, and eastern Central America occur less frequently during El Niño years (Gray, 1984).” Moreover, “warmer winter temperatures commonly are observed in the northern United States during El Niño, leading to less energy use and, therefore, lower energy prices (Chagnon, 1999).”

Goddard and Dilley conclude, “between mitigating adverse climate effects and taking advantage of beneficial ones through the prudent use of climate forecasts, El Niño and La Niña years may eventually result in substantially lower socioeconomic losses, globally, than are realized in other years.” Even in the absence of such actions, their work (and that of many other researchers) reveals there is little to fear during extreme ENSO years as compared to ENSO-neutral years.

References

- Brichetti, P., Foschi, U.F., and Boano, G. 2000. Does El Niño affect survival rate of Mediterranean populations of Cory’s Shearwater? *Waterbirds* **23**: 147–154.
- Chagnon, S.A. 1999. Impacts of 1997–98 El Niño-generated weather in the United States. *Bulletin of the American Meteorological Society* **80**: 1819–1827.
- De Lange, W.P. and Gibb, J.G. 2000. Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **34**: 419–434.
- Elsner, J.B. Bossak, B.H., and Niu, X.F. 2001. Secular changes to the ENSO-U.S. Hurricane Relationship. *Geophysical Research Letters* **28**: 4123–4126.
- Goddard, L. and Dilley, M. 2005. El Niño: catastrophe or opportunity. *Journal of Climate* **18**: 651–665.
- Gray, W.M. 1984. Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Monthly Weather Review* **112**: 1649–1668.
- Higgins, R.W., Leetmaa, A., and Kousky, V.E. 2002. Relationships between climate variability and winter temperature extremes in the United States. *Journal of Climate* **15**: 1555–1572.
- Hudak, D.R. and Young, J.M.C. 2002. Storm climatology of the southern Beaufort Sea. *Atmosphere-Ocean* **40**: 145–158.
- Kuhnel, I. and Coates, L. 2000. El Niño-Southern Oscillation: related probabilities of fatalities from natural perils in Australia. *Natural Hazards* **22**: 117–138.
- Muller, R.A. and Stone, G.W. 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast U.S. coast. *Journal of Coastal Research* **17**: 949–956.
- Pielke Jr., R.A. and Landsea, C.N. 1999. La Niña, El Niño, and Atlantic hurricane damages in the United States. *Bulletin of the American Meteorological Society* **80**: 2027–2033.
- Schwartz, R.M. and Schmidlin, T.W. 2002. Climatology of blizzards in the conterminous United States, 1959–2000. *Journal of Climate* **15**: 1765–1772.
- Singh, O.P., Ali Khan, T.M., and Rahman, M.S. 2000. Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorology and Atmospheric Physics* **75**: 11–20.
- Wilson, R.M. 1999. Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950–1998): implications for the current season. *Geophysical Research Letters* **26**: 2957–2960.

5

Observations: The Cryosphere

Donald J. Easterbrook (USA)

Clifford D. Ollier (Australia)

Robert M. Carter (Australia)

Key Findings

Introduction

5.1 Glacial Dynamics

5.2 Glaciers as Paleo-Thermometers

5.3 Modern Global Ice Volume and Mass Balance

5.4 Antarctic Ice Cap

5.5 Greenland Ice Cap

5.6 Other Arctic Glaciers

5.7 The Long Ice Core Record

5.8 Ice-sheet Mass Balance

5.8.1 Through Geological Time

5.8.2 Modern Measurements

5.8.3 Stability of the Antarctic Ice Sheet

5.8.4 Stability of the Greenland Ice Sheet

5.9 Mountain Glaciers

5.9.1 Holocene Glacial History

5.9.2 European Alpine Glaciers

5.9.3 Asia: Himalayan Glacier History

5.9.4 African Glaciers

5.9.5 South America

5.9.6 North America

5.10 Sea and Lake Ice

5.10.1 Arctic Sea Ice

5.10.2 Antarctic Sea Ice

5.10.3 Lake Ice

5.11 Late Pleistocene Glacial History

5.12 Holocene Glacial History

Key Findings

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice in glaciers, icecaps, and sea ice. Worries about untoward melting of the cryosphere in response to carbon dioxide-forced temperature rise have existed since the earliest days of global warming alarm in the 1980s.

- Satellite and airborne geophysical datasets used to quantify the global ice budget are short and the methods involved in their infancy, but results to date suggest both the Greenland and Antarctic Ice Caps are close to balance.

- Deep ice cores from Antarctica and Greenland show climate change occurs as both major glacial-interglacial cycles and as shorter decadal and centennial events with high rates of warming and cooling, including abrupt temperature steps.
- Observed changes in temperature, snowfall, ice flow speed, glacial extent, and iceberg calving in both Greenland and Antarctica appear to lie within the limits of natural climate variation.
- Global sea-ice cover remains similar in area to that at the start of satellite observations in 1979, with ice shrinkage in the Arctic Ocean since then being offset by growth around Antarctica.

Climate Change Reconsidered II

- During the past 25,000 years (late Pleistocene and Holocene) glaciers around the world have fluctuated broadly in concert with changing climate, at times shrinking to positions and volumes smaller than today.
- This fact notwithstanding, mountain glaciers around the world show a wide variety of responses to local climate variation, and do not respond to global temperature change in a simple, uniform way.
- Tropical mountain glaciers in both South America and Africa have retreated in the past 100 years because of reduced precipitation and increased solar radiation; some glaciers elsewhere also have retreated since the end of the Little Ice Age.
- The data on global glacial history and ice mass balance do not support the claims made by the IPCC that CO₂ emissions are causing most glaciers today to retreat and melt.
- No evidence exists that current changes in Arctic permafrost are other than natural or that methane released by thawing would significantly affect Earth's climate.
- Most of Earth's gas hydrates occur at low saturations and in sediments at such great depths below the seafloor or onshore permafrost that they will barely be affected by warming over even one thousand years.

Introduction

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice. The cryosphere forms the frozen part of the larger hydrosphere, which encompasses all the water contained in rain, rivers, lakes, and oceans. The processes and characteristics of the cryosphere and hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, the hydrosphere and cryosphere also change in response to external climate change forcings, some of which may be natural (e.g., changed solar insolation) and some of human origin (e.g., industrial greenhouse gas forcing). This distinction, which applies to all aspects of Earth's climate system, is easy to draw in principle, but in practice it has

proved difficult to establish that any specific changes in the cryosphere or hydrosphere documented over the past century have their origins in human activity.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC) commented, "recent decreases in ice mass are correlated with rising surface air temperatures. This is especially true in the region north of 65°N, where temperatures have increased by about twice the global average from 1965 to 2005" (IPCC 2007, p. 339). The IPCC went on to report decreased snow cover "in most regions, especially in spring and summer," freeze-up dates in the Northern Hemisphere occurring later, breakup dates occurring earlier, declines in sea-ice extent, and similar findings. All of these statements were made against the background assumption that the warming was of anthropogenic origin.

The authors of the 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC) and its 2011 interim report contended many of the IPCC's findings on this subject were incorrect, resulting from the inappropriate use of circumstantial evidence, cherry-picking of data, or misrepresentation of available research. Specifically, Idso and Singer (2009, p. 4) reported:

Glaciers around the world are continuously advancing and retreating, with a general pattern of retreat since the end of the Little Ice Age. There is no evidence of an increased rate of melting overall since CO₂ levels rose above their pre-industrial levels, suggesting CO₂ is not responsible for glaciers melting.

Sea ice area and extent have continued to increase around Antarctica over the past few decades. Evidence shows that much of the reported thinning of Arctic sea ice that occurred in the 1990s was a natural consequence of changes in ice dynamics caused by an atmospheric regime shift, of which there have been several in decades past and will likely be several in the decades to come, totally irrespective of past or future changes in the air's CO₂ content. The Arctic appears to have recovered from its 2007 decline.

By themselves such facts as melting glaciers and Arctic sea ice, while interesting, tell one nothing about causation. Any significant warming, whether anthropogenic or natural, will melt ice. To claim anthropogenic global warming (AGW) is occurring based on such information is to confuse the consequences of warming with its cause, constituting

Observations: The Cryosphere

an error in logic. Similar arguments apply also to fluctuations in glacier mass, sea ice, precipitation, and sea level, all of which can be forced by many factors other than temperature change. It is entirely inappropriate to use this type of circumstantial evidence to claim allegedly dangerous human-caused warming is occurring.

This chapter builds on the earlier NIPCC conclusions, bringing up to date our summary of the extensive scientific literature on global warming as it might affect the cryosphere. We again find changes in glacier and sea-ice extent frequently occur in ways that contradict, and rarely reinforce, the claims of the IPCC and the projections of its climate models. Overall, new research conducted since 2007 reinforces NIPCC's 2009 interim summary and finds less melting of ice in the Arctic, Antarctic, and mountain glaciers than previously feared, and no melting at all that could be uniquely attributed to rising carbon dioxide levels.

Some of the key concepts of cryospheric science that are relevant to the climate change issue are presented in the remainder of this introduction to set the stage for the analysis that follows.

GLACIER MASS BALANCE

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation (snowfall) dominates in winter, ablation (melting, avalanching, calving) in summer. If the two are equal, the net mass balance of a glacier or icecap is zero and its snout or periphery will remain stable; otherwise, a glacier will grow in size (advance) if accumulation is the greater (positive mass balance) or shrink and retreat if ablation is the greater (negative mass balance). In this way, climatic factors control glacial behavior, changes in which can be used as indicators of changing climatic conditions over time.

MEASUREMENTS OF MODERN MASS BALANCE

Little data exists with which to accurately quantify glacial mass balance prior to the twenty-first century. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment); and ICESat (Ice Cloud and Land Elevation Satellite)—are in their infancy and often of doubtful accuracy, not least because of the complexity of the data processing needed to correct and interpret the data sets. Also, the data sets are so short they

inevitably fail to capture the full range of climatic multidecadal variability.

Correction of satellite data requires an accurate model of the shape of Earth as represented by a spheroidal Terrestrial Reference Frame (TRF). The inadequacy of current TRFs is acknowledged by the Jet Propulsion Laboratory (NASA), which plans to launch a Geodetic Reference Antenna in Space (GRASP) satellite in order to establish a more accurate TRF. Until the accuracy of the TRF has been improved in this or other ways, spaceborne geophysical studies of ice-sheet mass balance and sea-level change will remain uncertain.

ICE CORES

The ice sheets of Greenland and Antarctica contain a remarkable layered ice record of past climatic change back to 120,000 and almost 1 million years ago, respectively. Changing oxygen isotope ratios in the ice act as a proxy for ancient air temperature change; analysis of trapped gases allows the estimation of the CO₂ and CH₄ content of the former atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric physico-chemical parameters also can be determined.

The ice cores show the climate record is permeated by both gradual and rapid change. This includes not only the major glacial-interglacial cycles, but also abrupt climate swings with high short-term rates of warming and cooling. Pleistocene and Holocene fluctuations in glacial activity onland match the climatic events represented in ice cores (and correlative deep sea mud cores), establishing the fidelity of core data as a record of past climatic change.

A particularly important result from ice core studies is the observation that changes in ancient CO₂ lag the equivalent changes in temperature by up to a thousand years, so CO₂ increase cannot be the cause of the warmings documented in the cores.

RECENT HISTORIC EVIDENCE

Glaciers have advanced and retreated during alternating warm and cool climatic periods throughout geological history. Since the mid-nineteenth century, the overall trend is that glaciers have lost mass as the Earth warmed after the Little Ice Age (LIA). No “unprecedented warming” has occurred during the twentieth century. Many glaciers retreated strongly during the 1915–1945 warm period before major industrial CO₂ emissions, advancing again during the 1945–1977 cool period when CO₂ emissions were soaring. This is precisely the opposite of what would

have happened if human-related CO₂ emissions caused enhanced warming and melting.

ANTARCTICA

Antarctica covers 14 million km² in area, is 98 percent covered by glacial ice that averages 2.4 km in thickness, corresponds to 90 percent of the world's ice, and represents about 70 percent of the world's fresh water. Melting all Antarctic ice would raise sea level by about 72 m. The average daily temperatures at the South Pole and Vostock, respectively, are -49.4° C and -55.1° C. In order to melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0° C. This is not happening now, nor is it likely to happen soon. The main (east) Antarctic ice sheet has been cooling since 1957 and ice accumulation is increasing rather than decreasing. For the same period, since 1957, warming and ice melting have occurred along the West Antarctic Peninsula, which represents 13 percent of Antarctic Ice. This melting may have an oceanographic rather than a meteorological cause.

So far as we are able to measure it accurately, the Antarctic ice mass is effectively stable on the short historic (meteorological) time scale. On the longer-term climatic scale, Antarctic and nearby ice volume has fluctuated in parallel with millennial-scale climate variability, including ice shrinkage during the Medieval Warm Period to positions that have not been attained again today.

Three facts confirm the likely modern stability of the East Antarctic Ice Sheet: (1) the late twentieth century global warming expected to melt the icecap lay well within the bounds of natural variation and has now ceased; (2) were warming to resume, the probable regional response would be enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; and (3) despite the past few interglacials being up to 5° C warmer than was the Holocene, sediment cores adjacent to Antarctica provide no evidence for any dramatic breakups of the WAIS over the past few glacial cycles.

GREENLAND

The Greenland ice sheet is the second largest ice mass in the world, being 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km². The mean altitude of the ice surface is 2,135 m and the ice is nearly 3 km thick in central Greenland. Nonetheless, this represents only a small part (8 percent) of global ice volume and 7 m of sea-level equivalent. During the last glaciation 20,000 years ago, the Greenland

massif was part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Although temperatures in Greenland rose during the late twentieth century, they did not rise as fast or as high as they did during the previous natural warming in the 1920s–1930s. Further-more, the temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years, indicating recent warmth is not unprecedented and not necessarily caused by rising CO₂.

The Little Ice Age in Greenland lasted to 1918, helping to achieve a subsequent rate of warming there for 1918–1935 that was 70 percent greater than the rate of warming for 1978–2004. The mean rate-of-rise in atmospheric CO₂ during this period was almost five times greater during the more recent warming.

Recent satellite-borne geophysical measurements suggest Greenland, like Antarctica, is in a state of approximate mass balance, quite contrary to the alarmist tone of much public commentary. Modern changes in glacier activity or volume in Greenland have no necessary or likely relationship with anthropogenic global warming and are more probably natural.

OTHER ARCTIC GLACIERS

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO₂-induced global warming.

Abundant field evidence shows high Arctic glaciers did not uniformly waste away during the late twentieth century and changed precipitation was as common a cause of glacial change as was changed temperature. As some glaciers advanced, others retreated; in addition, a Jan Mayen Glacier advance was accompanied by warming rather than cooling.

To the degree glaciers present in particular regions have retreated over the past 150 years (e.g., the Canadian Arctic), this is no more than would be expected for glaciers emerging from the Little Ice Age and does not require CO₂ emissions as an additional explanation.

MOUNTAIN GLACIERS

Montane ice is a volumetrically trivial part of the cryosphere (0.6 percent) and represents just 45 cm of sea-level equivalent. Nonetheless, changes in mountain glaciers are important in human terms because the well-watered alpine meadows that occur down-valley from glacier termini have long attracted settlers, and because rivers emanating from glacial valleys are an important wider water resource.

Observations: The Cryosphere

Few quantitative observations of mountain glaciers exist prior to 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Over the past millennium, glaciers have advanced and retreated multiple times as Earth passed successively through the Medieval Warm Period, Little Ice Age, and twentieth century warming. For many of the glaciers that show twentieth century retreat, shrinkage generally started in the late nineteenth century, many decades before human-related CO₂ emissions could have been a factor.

Research on mountain glaciers worldwide has failed to provide evidence for unnatural glacial retreat in the late twentieth century forced by human carbon dioxide emissions. Instead, historic glacial change correlates with the de Vries (~208 year) and Gleissberg (~80 year) solar cycles or fluctuates in sympathy with multidecadal oscillations like the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO).

TROPICAL GLACIERS

African mountain glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights. Repeated allegations have been made that the icecap on Kenya's iconic Mt. Kilimanjaro is melting away because of human-caused global warming.

Similar glacier retreat has been occurring throughout the tropics since the late nineteenth century, including on Mts. Kilimanjaro, Kenya, and Rwenzori in Africa and glaciers in Peru and Bolivia. Studies show reduced precipitation and increased solar radiation (due to decreasing cloudiness) have been the dominant factors influencing ice wastage, which commenced long before human-related CO₂ emissions could have been the cause. Despite common assertions, warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

ARCTIC SEA ICE

It is often claimed that CO₂-induced global warming is melting sea ice, especially in the Arctic Ocean. Semi-permanent oceanic sea ice exists today near the North Pole, but fringing sea ice is an annual, seasonal feature in both the Arctic and around Antarctica. Such ice is susceptible to fast advance or retreat, depending

upon local oceanographic and atmospheric conditions. Major sea-ice changes are not uncommon and not necessarily a result of temperature change; often, pulses of warm ocean water or atypical wind motions play a greater role.

Historical records demonstrate Arctic sea ice has fluctuated in sympathy with past multidecadal cycles in temperature, including shrinking to an area similar to that of the 2007 minimum during periods of relative warmth in the 1780s and 1940s; the pattern is that of the well-known multidecadal climate rhythms such as the Atlantic Oscillation and the Arctic and Arctic Ocean Oscillations. Earlier still, about 8,000 years ago during the Holocene Climatic Optimum, temperatures up to 2.5° C warmer than today resulted in what was probably an almost ice-free Arctic Ocean.

Arctic sea-ice cover varies dramatically and naturally over quite short periods of time, and Arctic fauna and flora, including the iconic polar bear, are adapted to deal with the environmental exigencies that result. It has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or a human economic perspective. No convincing research study demonstrates the level of sea-ice in the Arctic Ocean stood at some "ideal" level prior to the Industrial Revolution.

ANTARCTIC SEA ICE

Satellite-mounted sensors document a growth in both pack ice and fast ice across the East Antarctic region since 1979. Between 1979 and 2008, sea ice increased in area by about half a million square kilometers: a 2–3 percent increase during winter and spring and a 5–7 percent increase during summer. Thus the recent trend toward decreasing sea ice in the Arctic since 1979 has been counterbalanced by increasing sea ice in Antarctica, for a net result of little overall change in global sea-ice area.

This result is not consistent with the climate models that project high latitude warming and decreases in polar sea-ice in both hemispheres.

LATE PLEISTOCENE AND HOLOCENE CHANGE

Geological studies establish that before and during the last deglaciation (between 15,000 and 11,500 years ago), multiple, intense, and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. An intrinsic variability of about 1,500 years, termed the Dansgaard-Oeschger rhythm,

exhibits a magnitude and intensity up to 20 times greater than warming over the past century.

Similar climatic rhythms continued over the Holocene (last 11,700 years), as seen in the record from Greenland ice cores. The four most important characteristics of the documented variability are: the presence of a temperature peak about 2.5° C warmer than today at ~8,000 y BP; a general cooling trend thereafter; the punctuation of the record by 1,500-year-long, alternating rhythms of warmer and colder climate (termed Bond Cycles, and probably of solar origin), the warm peaks of which exceeded late twentieth century warmth; and for more than 90 percent of the past 10,000 years temperature has been 1–3°C warmer than today.

THE CRYOSPHERE THROUGH DEEP TIME

The total amount of ice in the cryosphere varies from time to time in sympathy with Earth's always-changing climate. Sixty million years ago, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in both the Antarctic and Greenland began after 45 million years ago, although it was probably only about 10 million years ago that a major northern icecap started to accumulate. Global cooling from 3 million years ago onward resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene ice ages.

Throughout this process of high-latitude ice-cap growth, the precise location and size of ice masses worldwide depended upon the vicissitudes of both local and global climate. Never, for any significant period of time, was a stable, global "ice mass balance" attained. Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will again vary in sympathy.

There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation. Nor is there any scientific basis for the common, implicit assumption that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

CONTEXT FOR THE MODERN CRYOSPHERE

The geological record of past climate provides an essential context largely missing from discussions about modern ice- volume changes and their significance. The rate and magnitude of twentieth century warming were small compared to the

magnitude of the profound natural climate reversals that have occurred over the past 20,000 years. Most importantly, too, none of the documented late Pleistocene and Holocene climatic events was accompanied by significant parallel change in atmospheric levels of carbon dioxide. Furthermore, the rate of glacier retreat has not increased over the period of large increases in CO₂ emissions over the past 60 years.

The data on global glacial history and ice mass balance simply do not support the claims made by the IPCC that CO₂ emissions are causing most glaciers today to retreat and melt. Instead, the null hypothesis—that twentieth century warming reflected natural climatic variation—remains valid.

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Idso, C.D., Singer, S.F. and Carter, R.M. 2011. *Interim Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S. et al (Eds.) Cambridge, UK: Cambridge University Press.

5.1 Glacial Dynamics

Glaciers are masses of granular snow and ice formed by compaction and recrystallization of snowfall, lying largely or wholly on land and showing evidence of past or present movement. The transformation of snow into ice in thicknesses great enough to promote motion on land is important. In addition to low temperatures, precipitation is needed for glaciers to develop. Some polar areas have no glaciers because even though the climate is cold, little snowfall occurs and the conditions needed to convert snow into ice occur infrequently.

Because the formation and persistence of glaciers are directly linked to climate, their deposits and landforms provide evidence for interpretation of past climatic changes. Thus an understanding of glacial processes is important for the study of ancient climates.

Although ice is solid at atmospheric pressure, it has low shear strength and will readily deform

Observations: The Cryosphere

plastically under shear stresses beyond 1 kg/cm^2 , resulting in continuous plastic flow.

$$\epsilon \text{ (strain)} = k[\rho(\text{ice density}) g (\text{gravity}) t (\text{ice thickness}) \sin \alpha (\text{slope of ice surface})]^n$$

The constant (k) increases with temperature, as does the n^{th} power in this equation. Thus, plastic flow in ice is very sensitive to temperature—the warmer the ice, the more easily it deforms. Strain rates at 0°C may be 10 times greater than at -22°C . Temperate glaciers, which are near the pressure-melting point of ice, generally exhibit higher rates of plastic flow than do polar glaciers, whose temperature is well below the freezing point. As seen in the equation above, not only temperature but also ice thickness and the slope of the ice surface affect flow velocity. The thicker the ice, the faster it flows, and the steeper the ice surface, the faster it flows.

In addition to plastic flow, glaciers also move by sliding over their bed. Basal sliding of glaciers increases where subglacial meltwater is present, especially if the subglacial water is under hydrostatic pressure, which then reduces the effective weight of the overlying ice and diminishes friction. Basal sliding is thus greatest in temperate glaciers and may be absent in polar glaciers, which are frozen to their base.

In general glaciers grow, flow, and melt continuously, within the context of an overall annual mass budget of gains and losses that is not necessarily balanced over time. Snow falls on high ground, compacts, and becomes solid ice. More precipitation of snow forms another layer on the top, so the ice grows thicker by the addition of new layers at the surface. When the ice is thick enough it starts to flow plastically under the force of gravity.

The mechanism of glacier flow needs to be considered carefully. Ice does not simply slide on its base. Nonetheless, sliding is a significant contributor of downslope movement for some glaciers, varying between 0 percent for the Meserve Glacier (Antarctica) and 75 percent for the Athabaska Glacier (Canada) (Paterson, 1981; Holdsworth and Bull, 1970).

References

Holdsworth, G. and Bull, C. 1970. The flow law of cold ice; investigations on Meserve Glacier, Antarctica. International Symposium on Antarctic Glaciological Exploration (ISAGE), Hanover, New Hampshire, USA, 3–7 September 1968, pp. 204–216.

Paterson, W.S.B. 1981. *The Physics of Glaciers*. Pergamon Press, Oxford, England.

5.1.1 Plastic Flow

When stress in ice exceeds its elastic limit, ice becomes plastic; this allows limitless permanent deformation to occur, because the ice flows continuously under its own weight. Ice flows plastically by three mechanisms, namely:

- intergranular shifting,
- intragranular shifting, and
- recrystallization.

In intergranular shifting, differential movement takes place between ice grains by rotation and sliding between individual ice crystals. For intragranular shifting, movement occurs by gliding along basal planes within ice crystals; this is a significant mechanism of glacial flow, easy slippage occurring along planes parallel to the base of the crystals, where fewer atomic bonds need to be broken for translation to occur. Recrystallization of ice facilitates down-glacier transfer of material by creep. Pressure at grain boundaries can melt ice at the pressure melting temperature, and meltwater can then migrate to sites of lower pressure (in the down ice direction), where it refreezes. The net effect of these three processes is plastic flow of the ice.

Three factors determine the magnitude of plastic flow in ice, namely:

- creep is proportional to temperature;
- creep is proportional to ice thickness (i.e., to the stress produced by the weight of overlying ice); and
- creep is proportional to the slope of the ice surface.

The closer the temperature comes to the melting point, the greater is the creep rate. The creep rate at -1°C is about 1,000 times greater than at -20°C .

The stress law of creep means the thicker the ice, the faster the flow. In valley glaciers the upper 30 m of the glacier cannot flow, because the ice is brittle and cracks to form crevasses in the rigid ice that is carried along on the plastically flowing lower ice. Because they are near melting point, valley glaciers do not have to be very thick to flow—a little over

30 m may be sufficient. The depth of the crevasses marks the threshold between brittle and plastic ice—at which level the yield stress¹ is reached. By contrast, a great stress is required to cause flow if the temperatures are very low as in polar glaciers.

Though the direction of movement of the terminus of a glacier is the simplest indicator of where the balance of accretion and ablation lies, this in itself tells us nothing about the *cause* of any change.

Himalayan glaciers present a distinctive variation of the typical flow mode. Whereas many glaciers start from icecaps that flow to the terminus, with continuous flow from the snow-collecting area to the glacier snout, many of those in the Himalayas are avalanche-fed. Relief is so great, and the peaks are so sharp, that snow falling on the peaks reaches the glaciers in the valleys via avalanches. The growth of such glaciers depends not just on precipitation, then, but on the frequency of avalanches. It could happen, for example, that increased temperature in the mountains caused increased avalanching, thereby thickening the glaciers and causing increased flow.

References

- Chamberlin, R.T. 1928. Instrumental work on the nature of glacial motion. *Journal of Geology* **36**: 1–30.
- Cuffey, K.M. and Paterson, W.S.B. 2010. *The Physics of Glaciers*. Elsevier, Amsterdam.
- Glen, J.W. 1952. Experiments on the deformation of ice. *Journal of Glaciology* **2**: 111–114.
- Glen, J.W. 1955. The creep of polycrystalline ice. *Proceedings of the Royal Society A* **228**: 519–538.
- Glen, J.W. 1958a. Mechanical properties of ice. 1. The plastic properties of ice. *Philosophical Magazine Supplement* **7**: 254–265.
- Glen, J.W. 1958b. The flow law of ice. A discussion of the assumptions made in glacier theory, their experimental foundations and consequences. *Bulletin of the International Association of Scientific Hydrology* **47**: 171–183.
- Glen, J.W. 1974. *Physics of Ice*. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Cold Regions Sci. and Engineering Monograph II-C2a.
- Glen, J.W. 1975. *Physics of Ice*. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Cold Regions Sci. and Engineering Monograph II-C2b.
- Kamb, B. 1964. Glacier geophysics. *Science* **146**: 353–365.
- Kamb, B. 1970. Sliding motion of glaciers: theory and observation. *Reviews of Geophysics and Space Physics* **8**: 673–728.
- Kamb, B. 1972. Experimental recrystallization of ice under stress. Geophysical Monograph, American Geophysical Union **18**: 211–241.
- Kamb, B. and LaChapelle, E. 1964. Direct observation of the mechanism of glacier sliding over bedrock. *Journal of Glaciology* **5**: 159–172.
- Kamb, B., Engelhardt, H., and Harrison, W.D. 1979. The ice-rock interface and basal sliding process as revealed by direct observations in boreholes and tunnels. *Journal of Glaciology* **23**: 416–419.
- Nye, J.F. 1951. The flow of glaciers and ice-sheets as a problem in plasticity. *Proceedings of the Royal Society of London A* **207**: 554–572.
- Nye, J.F. 1952a. The mechanics of glacier flow. *Journal of Glaciology* **2**: 82–93.
- Nye, J.F. 1952b. A comparison between the theoretical and the measured long profiles of the Unteraar glacier. *Journal of Glaciology* **2**: 103–107.
- Nye, J.F. 1953. The flow law of ice from measurements in glacier tunnels, laboratory experiments and the Jungfraufirn borehole experiment. *Proceedings of the Royal Society of London A* **219**: 477–489.
- Nye, J.F. 1959. The motion of ice sheets and glaciers. *Journal of Glaciology* **3**: 493–507.
- Nye, J.F. 1960. The response of glaciers and ice sheets to seasonal and climatic changes. *Proceedings of the Royal Society A* **256**: 559–584.
- Ollier, C.D. 2010. Glaciers—science and nonsense. *Geoscientist* **20** (March): 16–21.
- Ollier, C. and Pain, C. 2009. Why the Greenland and Antarctic ice sheets are not collapsing. *Australian Institute of Geologists Newsletter* **97**: 20–24.
- Paterson, W.S.B. 1981. *The Physics of Glaciers*. Pergamon Press, Oxford, England.
- Paterson, W.S.B. 1994. *The Physics of Glaciers* (3rd ed.). Pergamon Press, Oxford.
- Sharp, R.P. 1951. Features of the firn on upper Seward Glacier, St. Elias Mountains, Canada. *Journal of Geology* **59**: 599–621.

¹ The *yield stress* in ice is the stress above which behavior changes from that of a solid with brittle (elastic) properties to a material with ductile flow.

Sharp, R.P. 1953. Deformation of a vertical bore hole in a piedmont glacier. *Journal of Glaciology* 2: 182–184.

Sharp, R.P. 1989. *Living Ice: Understanding Glaciers and Glaciation*. Cambridge University Press, Cambridge, England.

Shumski, P.A. 1964. *Principles of Structural Glaciology*. Dover Publications, New York, NY.

Weertman, J. 1983. Creep deformation of ice. *Annual Review of Earth and Planetary Sciences* 11: 215–240.

5.2 Glaciers as Paleo-thermometers

Temperature not only affects flow rates in glaciers but also plays a critical role in the accumulation and ablation of snow and ice that control whether glacier termini advance or retreat.

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation dominates in the winter, ablation in the summer. If the two are equal, then the net balance of the glacier is zero; if accumulation is greater, the net balance will be positive; and if ablation is greater, the net balance will be negative.

A glacier having a protracted negative net mass balance loses ice not only by retreat of the terminus but also by substantial thinning or downwasting of the glacier. Because rates of glacial movement are a function of ice thickness, thinning of the ice reduces the rate of ice transfer down glacier, and the rate of retreat and downwasting increases. Thus, acceleration of terminal retreat in a glacier does not necessarily indicate accelerated climatic warming. Nonetheless, because climatic factors control accumulation and ablation rates, glaciers are often used as indicators of past climatic conditions. Figure 5.2.1 illustrates the relationship between climate and glacial response.

Reference

Easterbrook, D.J. 1993. *Glacial Processes; Surface Processes and Landforms*. Prentice Hall, p. 293–332.

5.3 Modern Global Ice Volume and Mass Balance

Ice is naturally present on Earth's surface in three main geomorphic forms: land-based icecaps (Greenland and Antarctica), mountain-valley glaciers, and floating sea ice. Today, nearly 30 million km³ (91 percent) of all land ice is in Antarctica, 2.6 million km³ (8 percent) is in Greenland; all other valley glaciers added together have a volume a little less than 0.2 million km³ (0.6 percent) (Poore *et al.*, 2011). Any consideration of the global ice budget, and changes within it, must start by acknowledging these bounding parameters of ice distribution.

Of the approximately 160,000 glaciers currently known to exist, only 67,000 (42 percent) have been inventoried to any degree (Kieffer *et al.*, 2000). Mass balance data (net positive for glacier growth, negative for shrinkage) exist for more than a single year for only just over 200 glaciers (Braithwaite and Zhang, 2000). When the length of record increases to five years, this number drops to 115; if both winter and summer mass balances are required, the number drops again to 79. Only 42 glaciers have records longer than 10 years. "That many glacierized regions of the world remain unsampled, or only poorly sampled" (Braithwaite and Zhang, 2000) represents a major problem for those wishing to undertake accurate global mass balance research.

Clearly, we know very little about the true state of most of the world's glaciers. Moreover, and despite media alarmism about the issue, mountain glaciers worldwide contain just 45 cm of sea-level change equivalent, and their melting is therefore largely irrelevant to concerns about sea-level rise. Major sea-level change from melting ice depends practically on the relative ice balance of the large Antarctic (73 m sea-level equivalent) and Greenland (7 m sea-level equivalent) icecaps (Poore *et al.*, 2011).

It is useful to distinguish two main lines of evidence as to whether modern changes in the mass balance of the cryosphere are unusual. The first of these is a comparison of modern with historic and



Figure 5.2.1. Relationship between and among climate, accumulation/ablation, net mass balance, and position of a glacier terminus. Adapted from Easterbrook, D.J. 1993. *Glacial Processes; Surface Processes and Landforms*. Prentice Hall, pp. 293–332.

Holocene changes in mountain glaciers, back to 11,700 years BP. It is, for example, well established that major glacial advances occurred between the fifteenth and nineteenth centuries, during a period of colder global temperature known as the Little Ice Age (Broecker, 2001; Grove, 2001). Many records indicate widespread glacial retreat thereafter, as temperatures began to rise in the mid- to late-1800s, and many glaciers have since shrunk in size and returned to a position characteristic of their pre-Little Ice Age state.

Second is the question of whether modern glaciers and icecaps are in a uniform, or indeed accelerating, state of retreat, as many commentators have alleged. The detailed evidence regarding this is presented below under the appropriate headings. To date, however, no research has contradicted the findings of Dowdeswell *et al.* (1997) and Braithwaite (2002).

In an analysis of Arctic glacier mass balance, Dowdeswell *et al.* (1997) found that of the 18 glaciers with the longest mass balance histories, more than 80 percent displayed negative mass balances over their periods of record. In addition, “almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance.” Because of the multiple warm and cool periods of the past century—two periods of cooling (1880–1915 and 1945–1977) and two periods of warming (1915–1945 and 1978–1998)—glaciers have both advanced and retreated. No global warming has occurred since 1998 and glaciers appear to be in a transition period.

Braithwaite (2002) reviewed mass balance measurements of 246 glaciers made between 1946 and 1995, spanning both the 1946–1977 cool period and the 1978–1998 warm period. He found “several regions with highly negative mass balances in agreement with a public perception of ‘the glaciers are melting,’ but there are also regions with positive balances.” Within Europe, for example, he notes “Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980–95.” When results for the whole world are combined for this most recent period of time, Braithwaite notes “there is no obvious common or global trend of increasing glacier melt in recent years.”

The glacier with the longest mass balance record is the Storglaciaren glacier in northern Sweden. The first 15 years of its 50-year record showed a negative mass balance with little trend. Thereafter, however, its mass balance became positive during the latter part of the 1945–1977 cool period (Braithwaite and

Zhang, 2000).

Although glaciers have advanced and retreated during alternating warm and cool periods, since the Little Ice Age (LIA) glaciers have lost mass as Earth thawed. No “unprecedented warming” occurred in the latter part of the twentieth century. Rather, glaciers retreated strongly during the 1915–1945 warm period before major industrial CO₂ emission and advanced during the 1945–1977 cool period when CO₂ emissions were soaring—just the opposite of what should have happened if CO₂ caused global warming and glacial melting.

Conclusion

No substantive evidence exists that the rate of glacier retreat has increased over the past 70 years, a time of large increases in CO₂ emissions. The common claim that most glaciers are today retreating or melting in response to human carbon dioxide emissions is incorrect. The global data on glacial mass balance simply do not support the claims made by the IPCC that most glaciers are today retreating or melting.

References

- Braithwaite, R.J. 2002. Glacier mass balance: the first 50 years of international monitoring. *Progress in Physical Geography* **26**: 76–95.
- Braithwaite, R.J. and Zhang, Y. 2000. Relationships between interannual variability of glacier mass balance and climate. *Journal of Glaciology* **45**: 456–462.
- British Antarctic Survey (BAS) 2000. BEDMAP—A new ice thickness and subglacial topographic model of the Antarctic. www.antarctica.ac.uk/bas_research/data/access/bedmap/.
- Broecker, W.S. 2001. Glaciers that speak in tongues and other tales of global warming. *Natural History* **110** (8): 60–69.
- Dowdeswell, J.A., Hagen, J.O., Bjornsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommanney, C.S.L., and Thomas, R.H. 1997. The mass balance of circum-Arctic glaciers and recent climate change. *Quaternary Research* **48**: 1–14.
- Grove, J.M. 2001. The initiation of the “Little Ice Age” in regions round the North Atlantic. *Climatic Change* **48**: 53–82.
- Kieffer, H., Kargel, J.S., Barry, R., Bindenschadler, R., Bishop, M., MacKinnon, D., Ohmura, A., Raup, B., Antoninetti, M., Bamber, J., Braun, M., Brown, I., Cohen, D., Copland, L., DueHagen, J., Engeset, R.V., Fitzharris, B., Fujita, K., Haeberli, W., Hagen, J.O., Hall, D., Hoelzle,

Observations: The Cryosphere

M., Johansson, M., Kaab, A., Koenig, M., Konovalov, V., Maisch, M., Paul, F., Rau, F., Reeh, N., Rignot, E., Rivera, A., Ruyter de Wildt, M., Scambos, T., Schaper, J., Scharfen, G., Shroder, J., Solomina, O., Thompson, D., Van der Veen, K., Wohlleben, T., and Young, N. 2000. New eyes in the sky measure glaciers and ice sheets. *EOS: Transactions, American Geophysical Union* **81**: 265, 270–271.

Poore, R.Z., Williams, R.S., and Tracey, C. 2000 (revised 2011). Sea level and climate. United States Geological Survey (USGS) Fact Sheet 002–00. <http://pubs.usgs.gov/fs/fs2-00/>.

5.4 Antarctic Ice Cap

Antarctica covers 14.0 million km² (5.4 million sq mi) and is Earth's fifth-largest continent (see Figure 5.4.1). Glacial ice covers about 98 percent of Antarctica. It is the coldest, driest, and windiest continent and has the highest average elevation of all the continents. Antarctica has about 91 percent of the world's ice, representing about 70 percent of the world's fresh water.

Antarctica is also by far the coldest continent, with the coldest temperature ever recorded being -89.2 °C at the Russian Vostok Station on July 21, 1983. Temperatures in the interior are often -80°C with low precipitation, making Antarctica a frozen desert. The South Pole averages less than 10 cm of snow per year.

East Antarctica, the highest part of the continent, is covered by the East Antarctic Ice Sheet, which reaches thicknesses of 4,776 m with a mean thickness of 2,225 m. At its lowest point Antarctica is 2,480 m below sea level.

West Antarctica makes up a much smaller area and is covered by the West Antarctic Ice Sheet. The West Antarctic Peninsula extends northwest from the main continent (see Figure 5.4.1) and contains only a small proportion of the total ice in Antarctica.

The study of Antarctica's climate has provided valuable insights and spurred contentious debate over issues of global climate change. Climate model results project warming for polar regions under enhanced greenhouse gas emissions, leading many to anticipate Earth's polar regions will experience severe responses to rising CO₂ levels. Real-world data from Antarctica do not support such expectations. In the 2009 and 2011 NIPCC reports, scientific analyses are described that demonstrate nothing unusual, unprecedented, or unnatural about the present climate of the large Antarctic ice sheet.

Among the commonest lines of evidence cited for

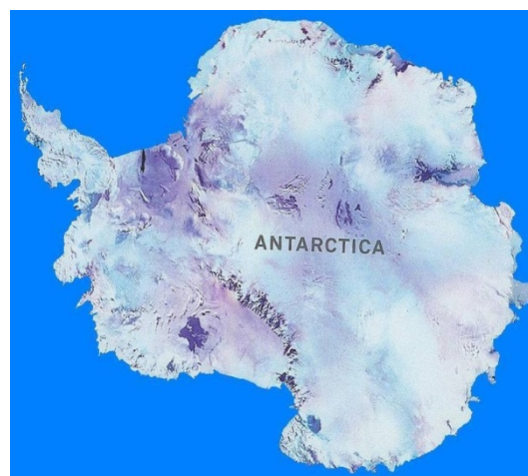


Figure 5.4.1. UPPER. Satellite view of the Antarctic Ice Sheet. LOWER. Digital terrain map of the subglacial rock topography of Antarctica, colorized as to height, after removal of the ice and correction for isostatic rebound and sea level change (NASA images).

unusual melting of Antarctic ice is the breaking away of large pieces of glacier termini or ice shelf. Warm ocean water around the West Antarctic Peninsula regularly causes some melting of ice and breaking off of pieces of shelf ice, but the volumes affected are only a small percentage of the main Antarctic ice sheet. The glaciological processes involved are entirely normal and natural; no evidence has been found to show the process of glacial calving around Antarctica is any different today than in the past.

For example, in November 2001 a large iceberg separated from West Antarctica's Pine Island Glacier. This event created great interest because the Pine Island Glacier is the fastest-moving glacier in Antarctica and discharges the largest volume of ice. Some speculated this event might herald the

“beginning of the end” of the West Antarctic Ice Sheet. Scientific studies suggest otherwise.

Rignot (1998) employed satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996 to determine whether it was advancing or retreating. The data indicated a retreat rate of 1.2 ± 0.3 kilometers per year over four years. Subsequently, Stenoien and Bentley (2000) used radar altimetry and synthetic aperture radar interferometry to prepare a velocity map of the ice catchment region, which revealed a system of tributary ice-flow streams that feed the main, fast-flowing trunk glacier. By combining velocity data with ice thickness and snow accumulation rates, they calculated an approximate mass balance for the glacier with an uncertainty of $\sim 30\%$. Their results suggested the mass balance of the catchment region was not significantly different from zero during recent years.

Hall (2009) concludes for many localities around Antarctica “ice extent was less than at present in mid-Holocene time,” suggesting “the magnitude of present ice recession and iceshelf collapse is not unprecedented.”

Evidence for previous ice shrinkage during warmer parts of the Holocene in the western Ross Sea region has been provided by Hall and Denton (1999, 2002) based on the distribution and dating of surficial and terrace deposits. Their research shows “the Wilson Piedmont Glacier was still less extensive than it is now” during the Medieval Warm Period. Together with Baroni and Orombelli (1994a), they also provided evidence for “an advance of at least one kilometer of the Hell’s Gate Ice Shelf within the past few hundred years.”

Hall and Denton conclude the Ross Sea area evidence suggests “late-Holocene climatic deterioration and glacial advance (within the past few hundred years) and twentieth century retreat.” Comparison with dated moraines elsewhere in the world shows the reported Wilson Glacier advance overlaps with similar Little Ice Age advances known from the South Shetland Islands (Birkenmajer, 1981; Clapperton and Sugden, 1988; Martinez de Pison *et al.*, 1996; Björck *et al.*, 1996), New Zealand (Wardle, 1973; Black, 2001), and even Europe.

Further support for a Holocene history punctuated by ice advance and retreat is provided by Hall’s (2009) comprehensive circum-Antarctic review, which found “glaciers on most if not all” of the Indian/Pacific-sector sub-Antarctic Islands “underwent advance in the last millennium, broadly synchronous with the Little Ice Age,” and “glaciers in

all areas” have “subsequently undergone recession,” but only in “the past 50 years.”

Tedesco and Monaghan (2010) studied records collected since the launch of passive microwave radiometers in 1979, finding for the past three decades the continent-wide snow and ice melting trend has been “negligible.” They also report between 1979 and 2009 snow and ice melt was at a “record” low, marking a “new historical minimum”; “December 2008 temperature anomalies were cooler than normal around most of the Antarctic margin”; and the “overall sea ice extent for the same month was more extensive than usual.”

Vaughan *et al.* (2003) note “historical observations since 1958 at Esperanza Station document warming equivalent to $3.5 \pm 0.8^\circ\text{C}$ per century,” marking the Antarctic Peninsula as among the most rapidly warming regions on Earth. To establish whether this warming is unusual in any way, Mulvaney *et al.* (2012) analyzed deuterium/hydrogen isotope ratios (δD) of an ice core from James Ross Island at the northeastern tip of the Antarctic Peninsula to develop a late glacial and Holocene temperature history for the region. They found the Antarctic Peninsula experienced a Holocene warm period 9,200–2,500 years ago, similar to modern-day levels. They also found “the high rate of warming over the past century is unusual (but not unprecedented) in the context of natural climate variability over the past two millennia.” More specifically, the temperature of James Ross Island has increased by $1.56 \pm 0.42^\circ\text{C}$ over the past 100 years, and at a rate of $2.6 \pm 1.2^\circ\text{C}$ over the past half-century. Mulvaney *et al.* conclude this is “highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era.”

Conclusions

These studies establish that on the shorter, meteorological time scale the Antarctic ice mass is effectively stable.

On the longer-term climatic scale, glacial activity on and around Antarctica has fluctuated in parallel with the millennial-scale ice volume variability evident throughout the world, including recession during the Medieval Warm Period to positions that have not been attained again today, followed by significant advances during the intervening Little Ice Age and recession again during the nineteenth and twentieth century natural warming episode.

Moreover, the modern warming of the Antarctic Peninsula falls within the bounds of natural variation during the Holocene.

References

- Baroni, C. and Orombelli, G. 1994a. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica. *Geology* **22**: 23–26.
- Baroni, C. and Orombelli, G. 1994b. Holocene glacier variations in the Terra Nova Bay area (Victoria Land, Antarctica). *Antarctic Science* **6**: 497–505.
- Birkenmajer, K. 1981. Lichenometric dating of raised marine beaches at Admiralty Bay, King George Island (South Shetland Islands, West Antarctica). *Bulletin de l'Academie Polonaise des Sciences* **29**: 119–127.
- Björck, S., Olsson, S., Ellis-Evans, C., Hakansson, H., Humlum, O., and de Lirio, J.M. 1996. Late Holocene paleoclimate records from lake sediments on James Ross Island, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* **121**: 195–220.
- Black, J. 2001. Can a Little Ice Age climate signal be detected in the Southern Alps of New Zealand? Masters Thesis, University of Maine.
- Clapperton, C.M. and Sugden, D.E. 1988. Holocene glacier fluctuations in South America and Antarctica. *Quaternary Science Reviews* **7**: 195–198.
- Hall, B.L. 2009. Holocene glacial history of Antarctica and the sub-Antarctic islands. *Quaternary Science Reviews* **28**: 2213–2230.
- Hall, B.L. and Denton, G.H. 1999. New relative sea-level curves for the southern Scott Coast, Antarctica: evidence for Holocene deglaciation of the western Ross Sea. *Journal of Quaternary Science* **14**: 641–650.
- Hall, B.L. and Denton, G.H. 2002. Holocene history of the Wilson Piedmont Glacier along the southern Scott Coast, Antarctica. *The Holocene* **12**: 619–627.
- Kreutz, K.J., Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., and Pittalwala, I.I. 1997. Bipolar changes in atmospheric circulation during the Little Ice Age. *Science* **277**: 1294–1296.
- Martinez de Pison, E., Serrano, E., Arche, A., and Lopez-Martinez, J. 1996. *Glacial geomorphology*. BAS GEOMAP 5A: 23–27.
- Mulvaney, R., Abram, N.J., Hindmarsh, R.C.A., Arrowsmith, C., Fleet, L., Triest, J., Sime, L.C., Alemany, O., and Foord, S. 2012. Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. *Nature* **489**: 10.1038/nature11391.
- Shepherd, A., Wingham, D.J., Mansley, J.A.D., and Corr, H.F.J. 2001. Inland thinning of Pine Island Glacier, West Antarctica. *Science* **291**: 862–864.
- Stenoien, M.D. and Bentley, C.R. 2000. Pine Island Glacier, Antarctica: A study of the catchment using interferometric synthetic aperture radar measurements and radar altimetry. *Journal of Geophysical Research* **105**: 21,761–21,779.
- Tedesco, M. and Monaghan, A.J. 2010. Climate and melting variability in Antarctica. *EOS, Transactions, American Geophysical Union* **91**: 1–2.
- Vaughan, D.G., Marshall, G.J., Connolley, W.M., Parkinson, C., Mulvaney, R., Hodgson, D.A., King, J.C., Pudsey, C.J., and Turner, J. 2003. Recent rapid regional climate warming on the Antarctic Peninsula. *Climatic Change* **60**: 243–274.
- Wardle, P. 1973. Variations of the glaciers of Westland National Park and the Hooker Range, New Zealand. *New Zealand Journal of Botany* **11**: 349–388.

5.5 Greenland Ice Cap

Only a small part of global ice volume is represented today by the Greenland Ice Cap (8 percent of the total), and during the last great glaciation, 20,000 years ago, the Greenland massif comprised an even smaller part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Despite its small size, an understanding of the controls on formation and melting of the Greenland Ice Cap remains important. Interest in Greenland and other Arctic ice-covered areas is also much enhanced by the nearby presence of Scandinavian and North American countries, whose citizens are alert to the conservation of their Arctic environment and its biota, including iconic species such as the polar bear.

The topographic map of the Greenland Ice Cap shows a broad dome, leading to the common assumption that the icecap is underlain by a dome-shaped continent. A map of the base of the ice shows this is not true. Instead a kilometer-deep basin extends below sea level under the Greenland interior, the sub-ice terrain being a bowl formed by a ring of mountains with few openings to the sea. This results from the mass of the icecap being heavy enough to cause isostatic sinking of the land.

Importantly, therefore, the ice cannot simply slide into the sea as is often alleged. Instead, ice near the base of the icecap flows upwards to join glaciers flowing through gaps in the mountain rim. According to the IPCC's *Fourth Assessment Report*, melting of the whole ice sheet would contribute nearly 7 m to sea-level rise (Bergmann *et al.* 2012). Yet if the whole ice sheet could suddenly melt, much of the water would be retained in a huge lake bounded by

the mountain rim. In any case, the distribution of annual mean temperatures on Greenland is such that melting is possible only around the periphery (Figure 5.5.1).

In 2006, several commentaries and articles in a celebrated issue of *Science* magazine described accelerating discharges of glacial ice from Greenland and gave dire warnings of an imminent large, rapid, and accelerating sea-level rise as one result (Bindshadler, 2006; Ekstrom *et al.*, 2006; Joughin, 2006; Kerr, 2006; Kennedy and Hanson, 2006; Otto-Bliesner *et al.*, 2006; Overpeck *et al.*, 2006). The center of the discussion was Ekstrom *et al.*'s identification of a 2002–2005 increase in micro-earthquakes beneath outflowing glaciers on the east and west coasts of Greenland, between approximately 65°N and 76°N latitude, which they argued indicated enhanced and potentially dangerous glacial flow.

The implied conclusion from the *Science* papers—that the changes were the result of human-caused global warming—was not shared by Joughlin (2006), who showed summer temperatures at locations within the glacial earthquake area were warmer during the 1930s than in 2002–2005. Joughlin concluded the period of recent warming in Greenland “is too short to determine whether it is an anthropogenic effect or natural variability.”

Przybylak (2000) published a comprehensive meteorological analysis that provides strong support for Joughin's conclusion, stating, “the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century” and citing corroborating evidence for an earlier warm Arctic in the 1930s and 1950s. Przybylak's concluded the meteorological record “shows that the observed variations in air temperature in the real Arctic are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect,” because “the temperature predictions produced by numerical climate models significantly differ from those actually observed.” These conclusions are supported by Greenland temperature records dating back to 1880 (Figure 5.5.2).

The studies discussed so far fail to take adequate account of the Holocene context within which modern glacial change must be considered. The record indicates warmer temperatures were the norm in Greenland in the earlier part of the past 4,000 years, including century-long intervals nearly 1° C warmer than the recent decade of 2001–2010 (Chylek *et al.*, 2004, 2006; Easterbrook, 2011). The current decadal mean temperature in Greenland has not exceeded the

envelope of natural variability over the past 4,000 years.



Figure 5.5.1. Mean annual temperature on the Greenland Ice Cap. Ice melting can only occur where the temperature exceeds the melting point. These conditions only occur at the edges of the icecap, where continued melting depends on glacially-slow flow to replace the melted ice. Adapted from Box, J.E., Yang, L., and Bromwich, D.H. 2009. Greenland Ice Sheet surface air temperature variability: 1840–2007. *Journal of Climate* 22: 4029–4049.

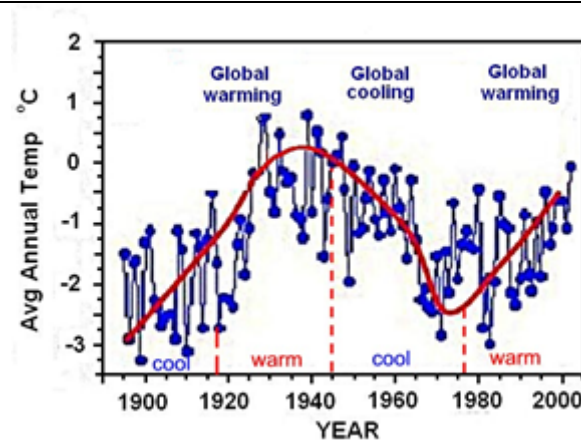


Figure 5.5.2. Temperatures in Angmagssalik, Greenland, since 1890, showing a multidecadal pattern of warmings and coolings. Note temperatures in the 1930s were higher than modern temperatures. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* 63: 201–221.

Observations: The Cryosphere

Kobashi *et al.* (2011) reconstructed high-resolution (~10 yr) records of the past 1,000 and past 160 years of Greenland's snow surface temperature, which also delineate clear multidecadal to multicentennial temperature fluctuations (see Figure 5.5.3). In keeping with more generalized climatic histories, these records are characterized by a warm period in the eleventh and twelfth centuries (the Medieval Warm Period), a long-term cooling toward the coldest period in the seventeenth and eighteenth centuries (the Little Ice Age), and the observed most recent warming (1978–2000).

Greenland underwent a 33 percent greater warming in 1919–1932 than the warming in 1994–2007 (Box *et al.*, 2009), and the recent decadal average temperature is similar to that of the 1930s–1940s (Chylek *et al.*, 2006; Box *et al.*, 2009). Kobashi *et al.* (2011) note the 2000–2010 decadal average surface temperature at the Greenland ice sheet summit, the warm period of the 1930s–1940s, and the Medieval Warm Period indicate “the present decade is not outside the envelope of variability of the last 1000 years.”

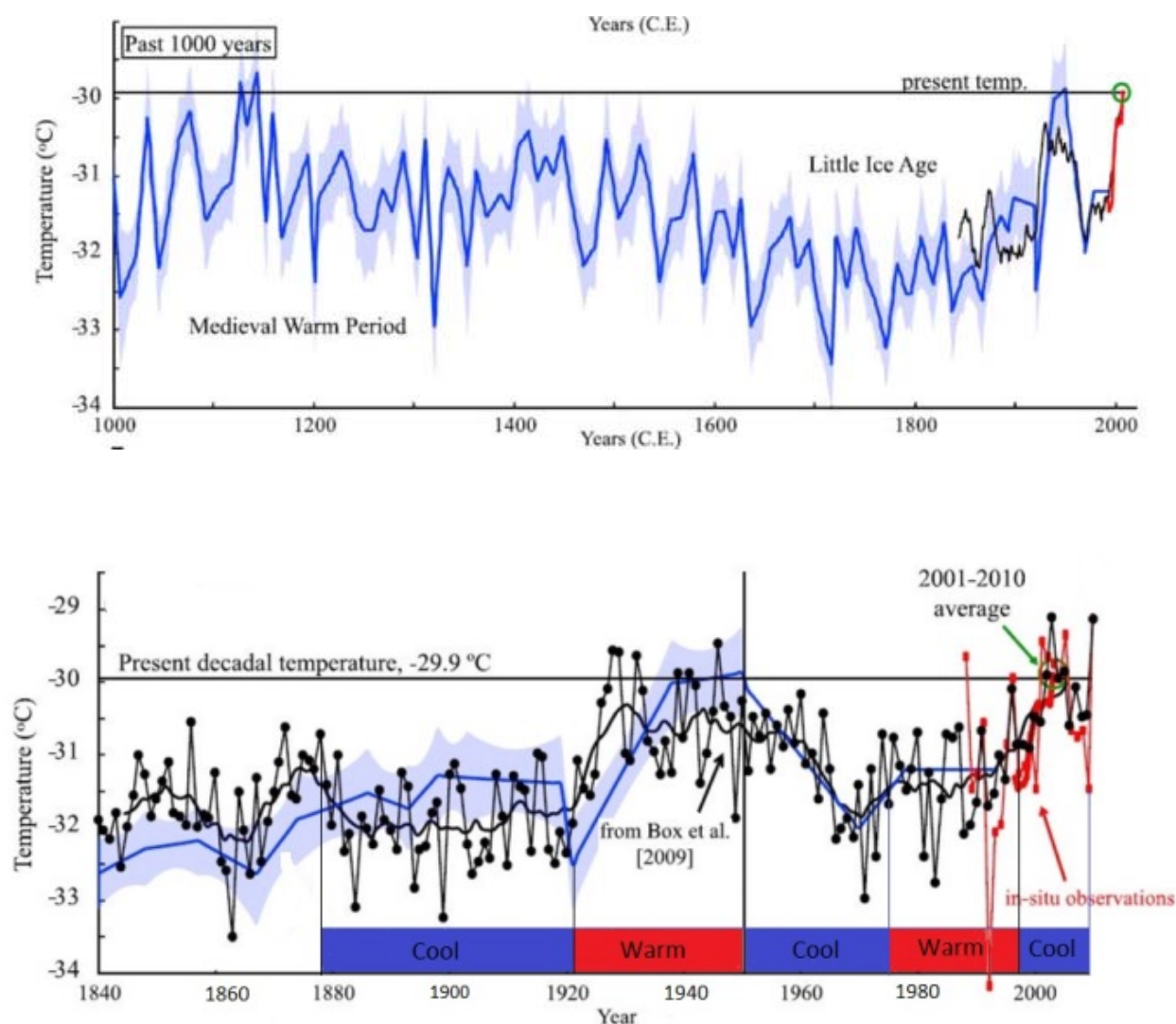


Figure 5.5.3. Reconstructed Greenland snow surface temperatures for the past 4000, 1,000 and 160 years. The alternating warm and cool periods correlate well with measured temperatures and other reconstructions. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

Conclusion

The temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years. Recent warmth is not unprecedented, and none of it was necessarily caused by rising CO₂.

References

- Bergmann, I., Ramillien, G., and Frappart, F. 2012. Climate-driven interannual ice mass evolution in Greenland. *Global and Planetary Change* **82–83**: 1–11. doi:10.1016/j.gloplacha.2011.11.005.
- Bindschadler, R. 2006. Hitting the ice sheets where it hurts. *Science* **311**: 1720–1721.
- Box, J.E., Yang, L., and Bromwich, D.H. 2009. Greenland Ice Sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.
- Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221.
- Chylek, P., Dubey, M. K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005: *Geophysical Research Letters* **33**: L11707.
- Easterbrook, D.J. 2011. Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future. In: Easterbrook, D.J. (Ed.) *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier, pp. 3–51.
- Ekstrom, G., Nettles, M., and Tsai, V.C. 2006. Seasonality and increasing frequency of Greenland glacial earthquakes. *Science* **311**: 1756–1758.
- Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., and Roberts, A.P. 2007. Continental ice in Greenland during the Eocene and Oligocene. *Nature* **446**: 176–179.
- Joughin, I. 2006. Greenland rumbles louder as glaciers accelerate. *Science* **311**: 1719–1720.
- Kennedy, D. and Hanson, B. 2006. Ice and history. *Science* **311**: 1673.
- Kerr, R.A. 2006. A worrying trend of less ice, higher seas. *Science* **311**: 1698–1701.
- Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.
- Otto-Bliesner, B.L., Marshall, S.J., Overpeck, J.T., Miller, G.H., Hu, A., and CAPE Last Interglacial Project members. 2006. Simulating Arctic climate warmth and icefield retreat in the last interglaciation. *Science* **311**: 1751–1753.
- Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Kiehl, J.T. 2006. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* **311**: 1747–1750.
- Przybylak, R. 2000. Temporal and spatial variation of surface air temperature over the period of instrumental observations in the Arctic. *International Journal of Climatology* **20**: 587–614.

Other research

A number of recent publications on the ice history of Greenland and nearby islands have demonstrated significant ice loss occurred in the twentieth century, in some part during periods of strong warming.

- Mernild *et al.* (2008) describe the 1993–2005 glacial history of Mittivakkat Glacier, on Ammassalik Island, Greenland, as having an overall “mass balance (that) has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% per year.” This and earlier ice loss occurred against the background of instrumental warmings recorded for 1918–1935 at 0.12°C per year and for 1978–2004 at 0.07°C per year.” These authors also report “the warmest average 10-year period within the last 106 years was the period from 1936–1946 (–1.8°C),” while the second warmest period was from 1995–2004 (–2.0°C). In addition, they note the period 1936–1946 was the warmest period within the last 106 years in West Greenland (Cappelen, 2004).
- Frauenfeld *et al.* (2011) also report Greenland ice melt has been increasing during the past three decades, with the melt extent observed in 2007 being the greatest on record as observed from satellite records. They comment the “total annual observed melt extent across the Greenland ice sheet has been shown to be strongly related to summer temperature measurements from stations located along Greenland’s coast, as well as to variations in atmospheric circulation across the North Atlantic.”

To test whether these changes might represent unprecedented modern (and anthropogenic) warming, Frauenfeld *et al.* reconstructed a record of annual ice melt extent across Greenland that extends back for 226 years, combining more recent satellite-derived observations with older melt extent values based upon historical observations of summer temperatures and winter circulation patterns. They conclude “the recent period of high-melt extent is similar in magnitude but, thus far, shorter in duration than a period of high melt lasting from the early 1920s through the early 1960s.” Although the greatest recorded melt extent did indeed occur in 2007, the occurrence was not statistically

Observations: The Cryosphere

significantly different from 20 older melt seasons, most during 1923–1961.

Frauenfeld *et al.* note “there is no indication that the increased contribution from the Greenland melt in the early to mid-20th century ... resulted in a rate of total global sea level rise that exceeded ~3 mm/yr.” Instead, their results indicate “Greenland’s contribution to global sea level rise, even during multi-decadal conditions as warm as the past several years, is relatively modest.”

- A common worry regarding ice wastage is that in summer surficial meltwater will penetrate through crevasses to lubricate faster flow at the base of the glacier (Iken and Bindshadler, 1986; Mair *et al.*, 2002; Truffer *et al.*, 2005; Bamber *et al.*, 2007; Bartholomew *et al.*, 2008; van de Wal *et al.*, 2008; Shepherd *et al.*, 2009; Schoof, 2010; Sundal *et al.*, 2011). Given that much glacier flow occurs by intracrystalline plastic processes, this worry is based on the speculative assumption of additional flow by sliding along the glacier-bedrock contact. Hoffman *et al.* (2011) have reported “basal lubrication by surface meltwater penetrating the Greenland Ice Sheet generates summer speedups of 50-200% for the regions of the ablation zone experiencing sheet flow.”

To investigate this phenomenon further, Hoffman *et al.* compared temperature measurements made at two weather stations; episodic supraglacial lake drainage events observed on Landsat images made at fortnightly intervals between early June and late August 2007; and ice velocity as recorded at nine GPS stations located across a 50 km swath of the western Greenland Ice Sheet. Calculation of strain rates and bed separation demonstrated the occurrence of “an early summer background period of constant ice velocity in west Greenland, followed by a speedup that lasted most of the summer and was associated with surface melt.” They also found “areas in the ablation zone typically experienced [only] one to two velocity events that are inferred to result from supraglacial lake drainage” and “in all cases the effects are short-lived (less than one day) and local (less than 10 km).” It is therefore unlikely rising temperatures are able to generate a positive feedback that causes significant glacial mass loss. Though Hoffman *et al.* say “episodic pulses of water are key for generating enhanced sliding,” they add “these daily increases in velocity are superimposed on a night time velocity that generally decreases over the season ... support(ing) the idea that rising air temperatures in Greenland may not translate directly into increased sliding at the seasonal scale.” Similar results have been reported by earlier writers,

including Zwally *et al.* (2002), Joughin *et al.* (2008), van de Wal *et al.* (2008), Shepherd *et al.* (2009), Bartholomew *et al.* (2010), Sundal *et al.* (2011), and Palmer *et al.* (2011).

Conclusions

It has been claimed that CO₂-induced global warming should be expressed most strongly in the Arctic, and its effects therefore should be evident there before anywhere else, making the Arctic the “canary in the coal mine” for those concerned about dangerous global warming. Though some localities in Greenland did indeed record significant ice retreat during the twentieth century, at other places, such as the Flade Isblink Ice Cap, ice accreted in sufficient amounts to cancel out the ice loss elsewhere.

The studies reported above make clear that any recent upswing in glacial outflow activity on Greenland has no necessary or likely relationship with anthropogenic global warming, as late twentieth century temperatures did not rise either as fast or as high as they did during the great natural warming of the 1920s–1930s.

The spectacular, and therefore often filmed, coastal glacial collapses or surficial meltwater streams plunging into crevasses represent only half of the equation relating to ice-sheet “collapse” and threatened sea-level change, the other half being the rate of inland ice accumulation derived from snow precipitation. Recent satellite radar altimetry suggests Greenland is in a state of approximate mass balance, quite contrary to the alarmist tone of the 2006 *Science* studies.

The argument that the modern Greenland Ice Cap is melting under the influence of anthropogenic warming is also greatly weakened by new stratigraphic evidence for Eocene-Oligocene ice in the Northern Hemisphere (Eldrett *et al.*, 2007), which is “about 20 million years earlier than previously documented, at a time when global deep water temperatures and, by extension, surface water temperatures at high latitude, were much warmer.” We now have evidence of a much warmer period of time during which the Greenland Ice Sheet failed to melt. In addition, “palaeoclimate model experiments generate substantial ice sheets in the Northern Hemisphere for the Eocene only in runs where carbon dioxide levels are lower (approaching the pre-anthropogenic level) than suggested by proxy records.”

The Little Ice Age lasted in Greenland until 1918, longer than it did in many other places, which doubtless helped to achieve a post-LIA rate of

warming between 1918 and 1935 some 70 percent greater than the warming from 1978 to 2004—even though the mean rate-of-rise of the atmosphere’s CO₂ concentration in the late twentieth century was nearly five times greater than during the 1920s–1930s warming. Greenland experienced more rapid warming in the earlier period of slow CO₂ rise, and slower warming in the latter period of rapid CO₂ rise.

References

Bamber, J.L., Alley, R.B., and Joughin, I. 2007. Rapid response of modern day ice sheets to external forcing. *Earth and Planetary Science Letters* **257**: 1–13.

Bartholomaeus, T., Anderson, R.S., and Anderson, S. 2008. Response of glacier basal motion to transient water storage. *Nature Geoscience* **1**: 33–37.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M.A., and Sole, A. 2010. Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. *Nature Geoscience* **3**: 408–411.

Cappelen, J. 2004. *Yearly Mean Temperature for Selected Meteorological Stations in Denmark, the Faroe Islands and Greenland; 1873–2003*. Technical Report 04-07 of the Danish Meteorological Institute, Weather and Climate Information Division, Copenhagen, Denmark.

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., and Roberts, A.P. 2007. Continental ice in Greenland during the Eocene and Oligocene. *Nature* **446**: 176–179.

Fischer, H., Wahlen, M., Smith, J., Mastroianni, D., and Deck, B. 1999. Ice core records of atmospheric CO₂ around the last three glacial terminations. *Science* **283**: 1712–1714.

Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784–2009. *Journal of Geophysical Research* **116**: 10.1029/2010JD014918.

Hoffman, M.J., Catania, G.A., Neumann, T.A., Andrews, L.C., and Rumrill, J.A. 2011. Links between acceleration, melting, and supraglacial lake drainage of the western Greenland Ice Sheet. *Journal of Geophysical Research* **116**: 10.1029/2010JF001934.

Iken, A. and Bindshadler, R. 1986. Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism. *Journal of Glaciology* **32**: 101–119.

Joughin, I., Das, S.B., King, M.A., Smith, B.E., Howat, I.M., and Moon, T. 2008. Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science* **320**: 781–783.

Joughin, I., Smith, B.E., Howat, I.M., Scambos, T., and Moon, T. 2010. Greenland flow variability from ice-sheet-wide velocity mapping. *Journal of Glaciology* **56**: 415–430.

Mair, D., Nienow, P., Sharp, M., Wohlleben, T., and Willis, I. 2002. Influence of subglacial drainage system evolution on glacier surface motion: Haut Glacier d’Arolla, Switzerland. *Journal of Geophysical Research* **107**: 10.1029/2001JB000514.

Mernild, S.H., Kane, D.L., Hansen, B.U., Jakobsen, B.H., Hasholt, B., and Knudsen, N.T. 2008. Climate, glacier mass balance and runoff (1993–2005) for the Mittivakkat Glacier catchment, Ammassalik Island, SE Greenland, and in a long term perspective (1898–1993). *Hydrology Research* **39**: 239–256.

Monnin, E., Indermuhle, A., Dallenback, A., Fluckiger, J., Stauffer, B., Stocker, T., et al. 2001. Atmospheric CO₂ concentrations over the last glacial termination. *Science* **291**: 112–114.

Palmer, S., Shepherd, A., Nienow, P., and Joughin, I. 2011. Seasonal speedup of the Greenland Ice Sheet linked to routing of surface water. *Earth and Planetary Science Letters* **302**: 423–428.

Schoof, C. 2010. Ice-sheet acceleration driven by melt supply variability. *Nature* **468**: 803–806.

Shepherd, A., Hubbard, A.L., Nienow, P., King, M.A., Mcmillan, M., and Joughin, I. 2009. Greenland ice sheet motion coupled with daily melting in late summer. *Geophysical Research Letters* **36**: 10.1029/2008GL035758.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Lagrend, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and the atmospheric history of the past 420,000 years from the Vostok Ice Core, Antarctica. *Nature* **399**: 429–436.

Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P. 2011. Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature* **469**: 521–524.

Truffer, M., Harrison, W.D., and March, R. 2005. Record negative glacier balances and low velocities during the 2004 heatwave in Alaska, USA: Implications for the interpretation of observations by Zwally and others in Greenland. *Journal of Glaciology* **51**: 663–664.

van de Wal, R., Boot, W., van den Broeke, M.R., Smeets, C.J.P.P., Reijmer, C.H., Donker, J.J.A., and Oerlemans, J. 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice Sheet. *Science* **321**: 111–113.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K.M., Saba, J., and Steffen, K. 2002. Surface melt-induced acceleration of Greenland Ice-Sheet flow. *Science* **297**: 218–222.

5.6 Other Arctic Glaciers

A perception existed until recently that high Arctic glaciers, especially those in Iceland and Svalbard (Spitzbergen), have been uniformly undergoing a reduction in ice volume since the mid-1990s.

Rinne *et al.* (2011) used satellite-borne radar altimetry to map elevation changes of the Flade Isblink Ice Cap (FIIC), northeast of Greenland, between 2002 and 2009. FIIC is the largest icecap in Greenland separate from the Greenland Ice Sheet, covering an area of 8,500 km². The measurements showed elevation gain (ice accretion) of up to 2 m/yr over most of the icecap, and elevation loss of up to 1 m/yr (ice melting) in lower, peripheral areas. The authors also reported a thickening, and inferred slowing of flow, of three outlet glaciers northeast of Station Nord. This confirmed the findings of Joughin *et al.* (2010), who, based on satellite-measured velocities, reported a slowdown from 300 m/year to 60 m/year for two of these glaciers between 2000 and 2006. Overall, Rinne *et al.* found “the net mass change rate of the FIIC to have been zero (0.0 ± 0.5 Gt/year) during 2002–2009.”

Rolsted Denby and Hulth (2011) used geodetic data derived from optical imaging back to 1949 to determine whether such reductions also applied to Jan Mayen Island, a 373-km² glaciated volcanic island located in the North Atlantic Ocean between Iceland and Svalbard at latitude 71° N. They found over the 33-year period 1975–2008 the ice volume in the southern part of Jan Mayen Island increased; there was also an increase in ice volume over the 59-year period 1949–2008, although the result was not statistically significant. These increases occurred despite a parallel increase in the annual mean temperature of the region by 1.58°C over the past 30 years, which drove a peripheral sea-ice retreat.

This combination of circumstances suggests where warming prevents winter sea-ice formation, the extra moisture made available by evaporation can enhance precipitation (in the form of snowfall) on coastal glaciers, and hence their growth even in a warming environment.

Moholdt *et al.* (2012) used data from the Ice, Cloud, and Land Elevation Satellite (ICESat) and the GRACE gravity satellites to assess the glacier mass budget between October 2003 and October 2009 for a

total glaciated area of 51,500 km² in the Russian High Arctic (Franz Josef Land, Severnaya Zemlya, and Novaya Zemlya). Their results were placed in a slightly longer-term climatic context by consideration of meteorological data from 1980 to 2009. As shown in Figure 5.6.1, significant glacial mass loss has occurred on Novaya Zemlya, less in Severnaya Zemlya, and a marginal increase in Franz Josef Land. All three records show a tendency for an increase in ice mass over the last two years. Of course, no hard conclusions can be reached on the basis of such a short and variable record; moreover, much uncertainty is attached to studies that utilize GRACE data because of the uncertainty of current geoid models (Houston and Dean, 2012).

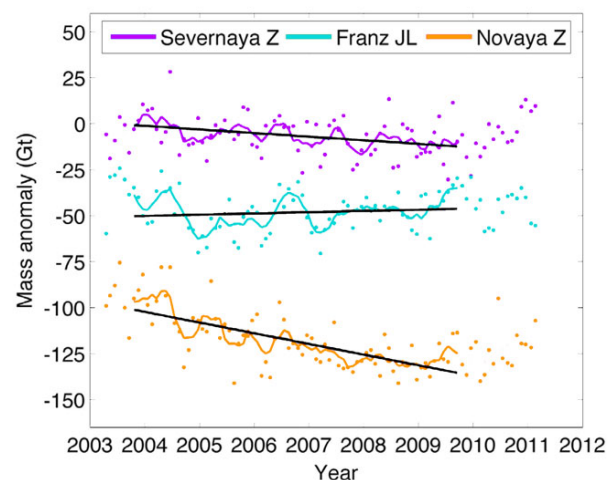


Figure 5.6.1. Monthly glacier mass anomalies (dots) as determined from GRACE, where colored curves are five-month running means of monthly data and black lines are linear fits to the monthly data within the ICESat for October 2003–October 2009. Adapted from Moholdt, G., Wouters, B., and Gardner, A.S. 2012. Recent mass changes of glaciers in the Russian High Arctic. *Geophysical Research Letters* **39**: 10.1029/2012GL051466.

References

- Houston, J.R. and Dean, R.G. 2012. Comparisons at tide-gauge locations of glacial isostatic adjustment predictions with global positioning system measurements. *Journal of Coastal Research* **28**(4): 739–744. doi:10.2112/JCOASTRES-D-11-00227.1.
- Moholdt, G., Wouters, B., and Gardner, A.S. 2012. Recent mass changes of glaciers in the Russian High Arctic. *Geophysical Research Letters* **39**: 10.1029/2012GL051466.

Rinne, E.J., Shepherd, A., Palmer, S., van den Broeke, M.R., Muir, A., Ettema, J., and Wingham, D. 2011. On the recent elevation changes at the Flade Isblink Ice Cap, northern Greenland. 2011. *Journal of Geophysical Research* **116**: 10.1029/2011JF001972.

Rolstad Denby, C. and Hulth, J. 2011. Assessment of differentiated surface elevation data from 1949, 1975 and 2008 for estimates of ice-volume changes at Jan Mayen. *Journal of Glaciology* **57**: 976-980.

Earlier research

Here we provide brief summaries of earlier published and NIPCC-summarized evidence for historic trends in Arctic glacier behavior, to see if it corresponds to the pattern of melting and retreat predicted by IPCC modeling.

- Dowdeswell *et al.* (1997) analyzed the mass balance records of the 18 Arctic glaciers with the longest observational histories, 80 percent of which displayed negative mass balances over their period of measurement. Ice core records from the Canadian High Arctic islands support this finding, and the researchers concluded the “generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age.”
- Calkin *et al.* (2001) provide a comprehensive review of Holocene glaciation along the northernmost Gulf of Alaska, between the Kenai Peninsula and Yakutat Bay. Several periods of glacial advance and retreat are identified over the past 7,000 years. A general ice retreat during the Medieval Warm Period lasted for “at least a few centuries prior to A.D. 1200,” after which the three major intervals of Little Ice Age—in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century—were accompanied by glacial expansion and depression of ice equilibrium-line altitudes by 150–200 m below present values.
- Zeeberg and Forman (2001) analyzed twentieth century changes in glaciers on north Novaya Zemlya—a Russian island located between the Barents and Kara Seas in the Arctic Ocean. Here, an accelerated post-Little Ice Age glacial retreat occurred in the first and second decades of the twentieth century. By 1952 the region’s glaciers had experienced 75 to 100% of their net twentieth century retreat, and during the next 50 years the recession of more than half of the glaciers stopped, while many tidewater glaciers began to advance. Instrumental records show the most recent of these glacial stabilizations and advances occurred in response to

increases in precipitation and/or decreases in temperature.

- Mackintosh *et al.* (2002) described the 300-year history of the Solheimajokull outlet glacier on the southern coast of Iceland. In 1705, this glacier had a length of about 14.8 km; by 1740 it had grown to 15.2 km in length, after which it retreated to a minimum length of 13.2 km in 1783. Rebounding rapidly, the glacier returned to its 1705 extent by 1794 and its 1740 length by 1820. This maximum length was maintained for the next half-century, after which the glacier contracted slowly to lengths of 14.75 km in 1932 and 13.8 km in 1970, after which rapid expansion occurred to 14.3 km by 1995. Currently, the glacier terminus falls about midway between its maximum and minimum positions of the past three centuries, and Mackintosh *et al.* report “the recent advance (1970–1995) resulted from a combination of cooling and enhancement of precipitation.”
- Humlum *et al.* (2005) evaluated the climate dynamics of high-latitude glaciers in the Svalbard Archipelago, especially the Longyearbreen glacier in arid central Spitzbergen (latitude 78°13’N). They found the Longyearbreen glacier “has increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years,” and they suggest this late-Holocene glacial growth is probably widespread in Svalbard and adjoining Arctic regions. Climate in Svalbard changed sharply more than once in the twentieth century, with Arctic-record rates of temperature rise in the early 1920s, followed by a nearly equivalent temperature drop four decades later. The Longyearbreen glacier changed in concert, and the current position of its terminus suggests this region of the Arctic is currently experiencing some of the lowest temperatures of the entire Holocene at a time of high atmospheric CO₂ concentration.
- In a late Holocene study, Bradwell *et al.* (2006) examined the link between fluctuations of Lambatungnajokull glacier, southeast Iceland, and variations in climate. Comparison between the glacial history and instrumental records show over the past four centuries “there is a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat”; recession was greatest during the 1930s and 1940s, when it averaged 20 m/year, but thereafter it slowed so “there has been little overall retreat since the 1980s.” The twentieth century part of this glacial history is shared by other nearby glaciers, consistent with the full 400-year history being typical for the wider region.

Conclusions

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO₂-induced global warming. These signs were expected to become especially evident in the second half of the twentieth century, when approximately two-thirds of the rise in industrial CO₂ emissions occurred and Earth's temperature allegedly rose to unprecedented levels.

The evidence is clear regarding these postulates: The many papers summarized above do not find high Arctic glaciers are uniformly wasting away. Instead, as some glaciers advance, others retreat, with the Jan Mayen example showing as well that some advances are actually accompanied by warming rather than cooling. Changed precipitation is as commonly a cause of glacial change as is changed temperature.

In particular, the findings of Humwell *et al.* (2005) and Bradwell *et al.* (2006) suggest in some Arctic regions twentieth century air temperatures peaked in the 1930s and 1940s, followed by a cooling that persisted through the end of the century. This thermal behavior is about as different as one could imagine from the steady warming claimed by the IPCC to have occurred around the globe through the twentieth century and especially over the last four decades. That empirical data from the Arctic should contradict this thesis so thoroughly is embarrassing for computer modellers, who have persistently predicted it is the high-latitude regions where anthropogenic global warming should be earliest and most strongly expressed. Clearly the real glacial world is more complex than IPCC computer models allow.

To the degree that in some regions (e.g., the Canadian Arctic) most glaciers have retreated over the past 150 years, this is no more than would be expected for glaciers emerging from the Little Ice Age. This circumstance does not require CO₂ emissions as an additional explanation.

References

- Bradwell, T., Dugmore, A.J., and Sugden, D.E. 2006. The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajokull, southeast Iceland. *Boreas* 35: 61–80.
- Calkin, P.E., Wiles, G.C., and Barclay, D.J. 2001. Holocene coastal glaciation of Alaska. *Quaternary Science Reviews* 20: 449–461.
- Dowdeswell, J.A., Hagen, J.O., Bjornsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner,

R.M., Lefauconnier, B., Ommanney, C.S.L., and Thomas, R.H. 1997. The mass balance of circum-Arctic glaciers and recent climate change. *Quaternary Research* 48: 1–14.

Humlum, O., Elberling, B., Hormes, A., Fjordheim, K., Hansen, O.H., and Heinemeier, J. 2005. Late-Holocene glacier growth in Svalbard, documented by subglacial relict vegetation and living soil microbes. *The Holocene* 15: 396–407.

Mackintosh, A.N., Dugmore, A.J., and Hubbard, A.L. 2002. Holocene climatic changes in Iceland: evidence from modeling glacier length fluctuations at Solheimajokull. *Quaternary International* 91: 39–52.

Zeeberg, J. and Forman, S.L. 2001. Changes in glacier extent on north Novaya Zemlya in the twentieth century. *Holocene* 11: 161–175.

5.7 The Long Ice Core Record

The large ice sheets of Antarctica and Greenland contain a remarkable record of past climatic changes, accumulated in their layered ice over tens to hundreds of thousands of years (Figure 5.7.1).

These deep ice cores have yielded much critical information about past climatic changes. The ¹⁸O/¹⁶O ratios in the ice can be used to identify past climatic changes, including proxy air temperature; analysis of trapped gases in the ice allows estimation of the ancient CO₂ content of the atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric parameters can also be determined from the ice.

The ice core data clearly show the climate record is permeated and punctuated by rapid climate changes, including short, abrupt climate swings with surprisingly high rates of warming and cooling (e.g., Steffenssen *et al.*, 2008). That the ice core data are indeed a proxy for global climate change is apparent because fluctuations of glaciers all over the world match the climatic events shown in both deep sea mud cores and other ice cores. These results notwithstanding, some scientists remain skeptical of the accuracy of geochemical measurements made in ice cores because of envisaged problems of post-depositional gas migration and ice bubble diffusion, leakage, and fractionation (e.g., Jaworowski *et al.*, 1992).

The most precisely dated ice cores are from the Greenland Ice Sheet Project (GISP) and Greenland Ice Core Project (GRIP). These cores are especially important because the age of the ice at various levels in the core can be measured by counting annual layers

Climate Change Reconsidered II

in the ice, giving a very accurate chronology. The GISP2 Greenland ice core has proven to be a great source of climatic data from the geologic past. The oxygen isotope ratios of thousands of ice core samples were measured by Minze Stuiver and Peter Grootes at the University of Washington (e.g., Grootes and Stuiver, 1997), and these data have delineated what has become to be accepted as a world standard climatic record.

The ratio of ^{18}O to ^{16}O in an ice core sample depends upon the temperature when the snow crystallized and is later transformed into glacial ice. Ocean volume also may play a role in $\delta^{18}\text{O}$ values, but these measurements nonetheless provide a good proxy for ancient temperature, with the age of each sample being accurately known from annual dust layers in the ice core.

Changes in carbon dioxide content lag their equivalent temperature events by between several

hundred and 2,000 years in Antarctic ice cores (see Figures 5.7.1 and 5.7.2). Changes in carbon dioxide level cannot be the proximate cause of the warmings and coolings seen. Fischer *et al.* (1999) established CO_2 lagged temperature by 600 ± 400 years as the climate warmed from an ice age. Monnin *et al.* (2001) found warming from the last major ice age preceded rise in CO_2 by 800 ± 600 years. Caillon *et al.* (2003) documented that rise in temperature preceded rise in CO_2 in the Vostok core by 800 ± 200 years. Mudelsee (2001) recognized temperature over the past 420,000 years preceded changes in CO_2 by $1,300 \text{ years} \pm 1,000$ in the Vostok core. Petit *et al.* (1999) analyzed 420,000 years of the Vostok core and found as the climate cooled into an ice age, the CO_2 decrease lagged by several thousand years.

Measurements of recent and modern temperature and CO_2 changes show the same lead-lag effect (Figure 5.7.3).

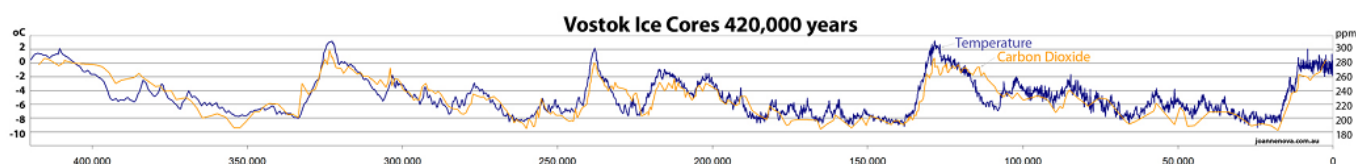


Figure 5.7.1. Temperature and CO_2 for 100,000–150,000 years ago from the Vostok ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. Reprinted from Joanne Nova, 2013, <http://joannenova.com.au/global-warming-2/ice-core-graph/>.

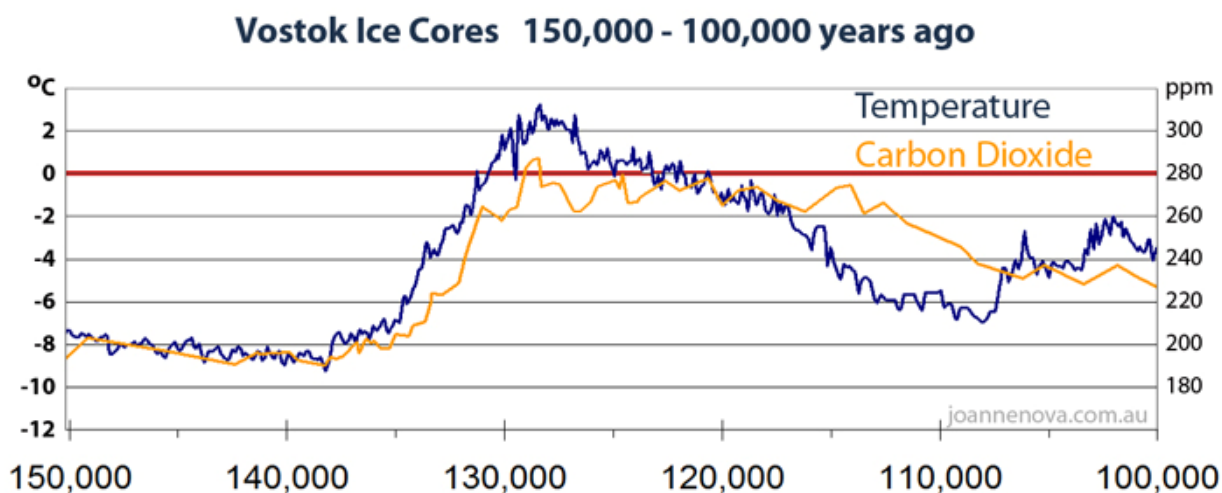


Figure 5.7.2. Temperature and CO_2 levels detail for 100,000–150,000 years ago from the Vostok ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. From Joanne Nova, 2013, <http://joannenova.com.au/global-warming-2/ice-core-graph/>.

Observations: The Cryosphere

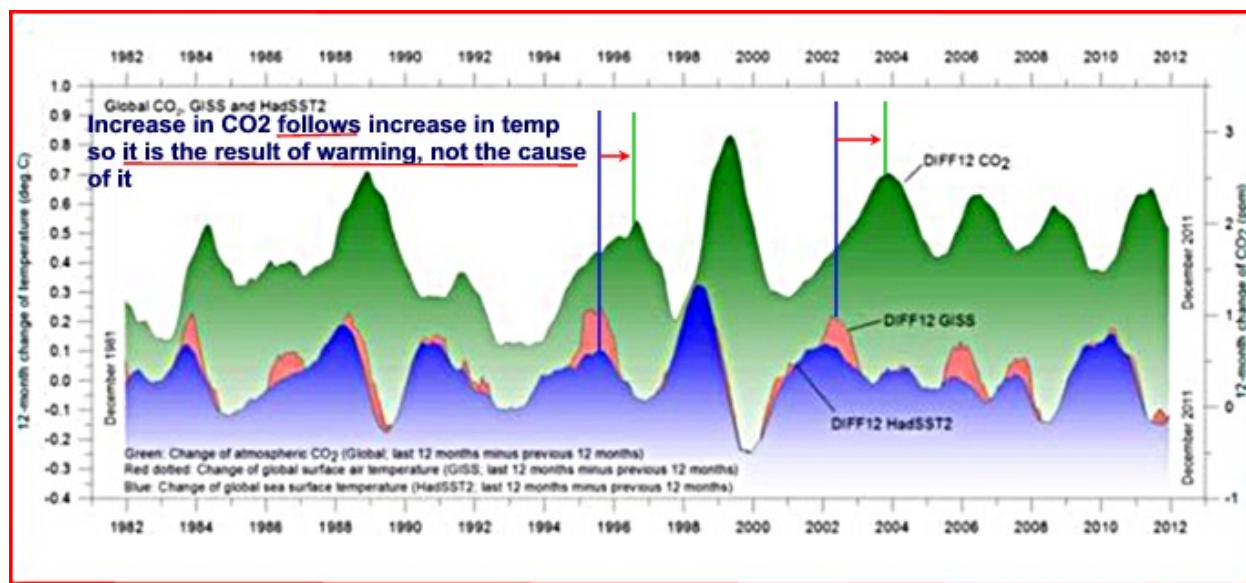


Figure 5.7.3. Lead-lag relationship of increased temperature and increased CO₂ over historic time. Adapted from Humlum, O., Stordahl, J., and Solheim, J. 2012. The phase relation between atmospheric carbon dioxide and global temperature. *Global and Planetary Change* **100**: 51–69. <http://dx.doi.org/10.1016/j.gloplacha.2012.08.008>.

Conclusion

Changes in atmospheric carbon dioxide levels lag temperature change by at least many hundred years. The studies reviewed here make it clear CO₂ cannot be the cause of the warmings seen in ice cores.

References

- Caillon, N., Severinghaus, J.P., Jouzel, J., Barnola, J.-M., Kang, J., and Lipenkov, V.Y. 2003. Timing of atmospheric CO₂ and Antarctic temperature changes across Termination III. *Science* **299**: 1728–1731.
- Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396.
- Grootes, P.M. and Stuiver, M., 1997. Oxygen 18/16 variability in Greenland snow and ice with 10³ to 10⁵-year time resolution. *Journal of Geophysical Research* **102**: 26,455–26,470.
- Humlum, O., Stordahl, J., and Solheim, J. 2012. The phase relation between atmospheric carbon dioxide and global temperature. *Global and Planetary Change* **100**: 51–69. <http://dx.doi.org/10.1016/j.gloplacha.2012.08.008>.
- Jawarowski, Z., Segalstad, T.V., and Hisdal, V. 1992. Atmospheric CO₂ and global warming: a critical review. *Meddelelser* **119**: 1–76.
- Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.
- Steffensen, J.P., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Goto-Azuma, K., Hansson, M.J., Sigfus, J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S.O., Roethlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M., Sveinbjornsdottir, A.E., Svensson, A., and White, J.W.C. 2008. High-resolution Greenland ice core data show abrupt climate change happens in few years. *Science* **321**: 680–684.
- Stuiver, M., Grootes, P.M., and Brasiunas, T.F. 1995. The GISP2 $\delta^{18}\text{O}$ record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* **44**: 341–354.

5.8 Ice-sheet Mass Balance

5.8.1 Through Geological Time

Sixty million years ago, during the warm Paleogene period, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in the Antarctic and Greenland began during a Late Eocene cooling after c. 45 million years ago (Kennett, 1977; Barker *et al.*, 2007; Tripathi *et al.*, 2008), though it was probably

only in the latest Miocene, c. 10 My ago, that a major northern icecap started to accumulate (Bartoli *et al.*, 2005).

Thereafter, global cooling after the latest Pliocene, c. 3 million years ago, resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene. Throughout this process of high-latitude icecap growth, the precise location and size of ice masses depended upon the vicissitudes of local and global climate. Never, for any significant period of time, was a stable, global “ice mass balance” attained, as noted in a recent paper by Naish *et al.* (2009) about the Antarctic ANDRILL project.

The ANDRILL site recovered a marine glacial record for the past 5 million years from the seabed beneath the northwest part of the Ross Ice Shelf. Sedimentary deposition and nearby glacial advance and retreat since the Pliocene have proceeded in sympathy with the background Milankovitch ~40-kyr cyclic variations in insolation controlled by changes in Earth’s axial tilt (obliquity). Naish *et al.* state, “the WAIS ... periodically collapsed, resulting in a switch from grounded ice, or ice shelves, to open waters in the Ross embayment when planetary temperatures were up to ~3°C warmer than today and atmospheric CO₂ concentration was as high as ~400 ppm” in one especially significant warming episode during marine isotope stage 31 (early Pleistocene, 1.085–1.055 My ago) leading to the deposition of open ocean foraminifer-coccolith-diatom ooze at the Ross Sea drillsite. The extra warm periods during the generally warmer early Pleistocene and Pliocene were clearly not primarily controlled by changes in the air’s CO₂ concentration; moreover, the growth (and decay) of ice sheets occurs in response to pervasive climate changes of both deterministic and stochastic nature.

Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will vary in sympathy. There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation. Nor is there any scientific basis for the common, implicit assumption that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

References

- Barker, P.F., Diekmann, B., and Escutia, C. 2007. Onset of Cenozoic Antarctic glaciation. *Paleoceanography and Paleoclimatology of the Southern Ocean: A Synthesis of Three Decades of Scientific Ocean Drilling* **54**: 2293–2307. doi:10.1016/j.dsr2.2007.07.027.
- Bartoli, G., Sarnthein, M., Weinelt, M., Erlenkeuser, H., Garbe-Schönberg, D., and Lea, D.W. 2005. Final closure of Panama and the onset of Northern Hemisphere glaciation. *Earth and Planetary Science Letters* **237**: 33–44. doi:10.1016/j.epsl.2005.06.020.
- Kennett, J.P. 1977. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography. *Journal of Geophysical Research* **82**: 3843–3860. doi:10.1029/JC082i027p03843.
- Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M., Wilson, T., Carter, L., DeConto, R., Huybers, P., McKay, R., Pollard, D., Ross, J., Winter, D., Barrett, P., Browne, G., Cody, R., Cowan, E., Crampton, J., Dunbar, G., Dunbar, N., Florindo, F., Gebbhardt, C., Graham, I., Hannah, M., Hansaraj, D., Harwood, D., Helling, D., Henrys, S., Hinnov, L., Kuhn, G., Kyle, P., Laufer, A., Maffioli, P., Magens, D., Mandernack, K., McIntosh, W., Millan, C., Morin, R., Ohneiser, C., Paulsen, T., Persico, D., Raine, I., Reed, J., Riesselman, C., Sagnotti, L., Schmitt, D., Sjunneskog, C., Strong, P., Taviani, M., Vogel, S., Wilch, T., and Williams, T. 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**: 322–328.
- Tripathi, A.K., Eagle, R.A., Morton, A., Dowdeswell, J.A., Atkinson, K.L., Bahe, Y., Dawber, C.F., Khadun, E., Shaw, R.M.H., Shorttle, O., and Thanabalasundaram, L. 2008. Evidence for glaciation in the Northern Hemisphere back to 44 Ma from ice-rafted debris in the Greenland Sea. *Earth and Planetary Science Letters* **265**: 112–122. doi:10.1016/j.epsl.2007.09.045.

5.8.2 Modern Measurements

Observational data prior to the twenty-first century is for the most part not available to systematically quantify the processes of glacial mass balance. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment; and ICESat (Ice Cloud, and Land Elevation Satellite)—are in their infancy and often of doubtful accuracy, not least because of the complexity of data processing necessary to render the raw measurements into useful results. In addition, the data sets are so

short that they inevitably fail to capture the full range of climatic multidecadal variability.

The GRACE gravity satellite uses radar ranging to measure land ice, a technique requiring accurate knowledge of an appropriate Glacial Isostatic Adjustment (GIA) model. Current GIA calculations for ice sheets are confounded by, among other things, an effect that creates an erroneous conclusion of ice loss when in reality there has been an ice increase (Irvin and James, 2005; Shum *et al.*, 2008; Tegoning *et al.*, 2009; King *et al.*, 2012).

More generally, data from the GRACE satellite have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and other factors. NASA's Jet Propulsion Laboratory is seeking support for the launch of a new space platform, the Geodetic Reference Antenna in Space (GRASP) satellite, the primary mission of which would be to establish an accurate TRF.

The limitations of GRACE interpretations of ice mass balance are well illustrated by two recent papers. The first, by King *et al.* (2012), notes recent estimates of Antarctic ice-mass change cannot be reconciled with each other within the cited formal errors. They cite inadequacy in the models of glacial isostatic adjustment (GIA) as a major cause and adopt a new GIA model with better geological constraints. Applying this model to 2002–2010 GRACE data, King *et al.* estimate a continent-wide ice-mass change of -69 ± 18 Gt/yr. This is about one-third to one-half of other recently published GRACE estimates based on older GIA models (Velicogna, 2009; Chen *et al.*, 2009; Zwartz, 2009), and it represents a $+0.19 \pm 0.05$ mm/yr sea-level change.

Alternatively, Shepherd *et al.* (2012) used “an ensemble of satellite altimetry, interferometry, and gravimetry data sets using common geographical regions, time intervals, and models of surface mass balance and glacial isostatic adjustment to estimate the mass balance of Earth's polar ice sheets” over the period 1992–2011. They estimate the polar ice sheets have contributed 0.59 ± 0.20 mm/yr to the rate of global sea-level rise, driven by individual changes of mass of -142 ± 49 Gt/yr in Greenland, $+14 \pm 43$ Gt/yr in East Antarctica, -65 ± 26 in West Antarctica, and -20 ± 14 Gt/yr in the Antarctic Peninsula.

Notwithstanding the careful and systematic analysis to which the data have been subjected, the uncertainty of these estimates is manifest in the cited

error bounds, which range from about 30% to almost 300% of the data value. Further uncertainty as to the relevance of the results is implicit in Shepherd *et al.*'s own caution that “assessments of mass imbalance based on short geodetic records should be treated with care, because fluctuations in surface mass balance can be large over short time periods,” not to mention that the time period surveyed represents just one-third of the known 60-year oceanographic cycle.

Until an adequate TRF has been established, papers that use GRACE data, including recent reviews of ice-sheet mass balance like those of King *et al.* (2012) and Shepherd *et al.* (2012), must be viewed as speculative “best interpretations” of the available, noisy data. However, and noting Earth has no intrinsic or “preferred” long-term ice mass balance (as discussed in Section 5.8.1), the fact that as yet we have no way of accurately measuring ice sheet dynamics does not lessen the intrinsic interest of studying historic and modelled changes in the planetary ice budget through time.

References

- Chen, J.L., Wilson, C.R., Blankenship, D., and Tapley, B.D. 2009. Accelerated Antarctic ice loss from satellite gravity measurements. *Nature Geoscience* 2: 859–862.
- Irvin, E.R. and James, T.S. 2005. Antarctic glacial isostatic adjustment; a new assessment. *Antarctic Science* 17: 541–553. doi: <http://dx.doi.org/10.1017/S0954102005002968>
- King, M.A., Bingham, R.J., Moore, P., Whitehouse, P.L., Bentley, M.J., and Milne, G.A. 2012. Lower satellite-gravimetry estimates of Antarctic sea-level contribution. *Nature* 491: 586–589. doi:10.1038/nature11621.
- Shepherd, A., Ivins, E.R., Geruo, A., Barletta, V.R., Bentley, M.J., Bettadpur, S., Briggs, K.H., Bromwich, D.H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M.A., Lenaerts, J.T.M., Li, J., Ligtenberg, S.R.M., Luckman, A., Luthcke, S.B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J.P., Paden, J., Payne, A.J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L.S., Scambos, T.A., Scheuchl, B., Schrama, E.J.O., Smith, B., Sundal, A.V., van Angelen, J.H., van de Berg, W.J., van den Broeke, M.R., Vaughan, D.G., Velicogna, I., Wahr, J., Whitehouse, P.L., Wingham, D.J., Yi, D., Young, D., and Zwally, H.J. 2012. A reconciled estimate of ice-sheet mass balance. *Science* 338: 1183–1189. doi:10.1126/science.1228102.
- Shum, C.K., Kuo, C.-y., and Guo, J.-y. 2008. Role of Antarctic ice mass balance in present day sea-level change. *Polar Science* 2: 149–161.

Tegoning, P., Ramillien, G., McQueen, H., and Velicogna, I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters* **36**: L19503.

Zwartz, D. 2009. Glacial isostatic adjustment and nonstationary signals observed by GRACE. *Journal of Geophysical Research* **114**: B06406. doi: 10.1029/2008JB006161.

5.8.3 Stability of the Antarctic Ice Sheet

5.8.3.1 Geological setting

The Antarctic ice sheet came into existence a little more than 40 million years ago, during the Eocene, and its size has fluctuated according to climatic conditions. Glacial ice in the Beacon Valley near the Taylor dome of the East Antarctic Ice Sheet lies beneath sediments that contain volcanic ash dated at 8.1 million years, indicating the glacier has existed throughout the Miocene and Pliocene to the present (Sugden *et al.*, 1995). Even though global temperatures were warmer in the Miocene and Pliocene than in the Quaternary, the Antarctic ice sheet has persisted, albeit at variable extent, for tens of millions of years.

In addition to the extremely cold temperature in Antarctica, a major reason for the stability of the Antarctic ice sheet is the circumpolar vortex, a strong circulation of winds that builds up during the winter months in the upper layers of the atmosphere around Antarctica, effectively isolating the continent from the rest of the world, keeping warm ocean waters away and temperatures low. An analogous circulation system in the ocean, the cold Antarctic Circumpolar Current (ACC), keeps warm sea water away from the Antarctic coast.

As Naish *et al.* (2009) have shown (Section 5.8.1), the Antarctic ice sheet has fluctuated in volume during its evolution, even as it grew progressively through the Plio-Pleistocene to attain its current (interglacial) size. Predictions of its imminent collapse reveal a lack of understanding that isostatic sinking causes both the Greenland and Antarctic icecaps to occupy bedrock depressions; for them to “slide into the sea” would require that they “slide” uphill.

References

Naish, T., Powell, R., Levy, R., Wilson, G., Scherer, R., Talarico, F., Krissek, L., Niessen, F., Pompilio, M.,

Wilson, T., Carter, L., DeConto, R., Huybers, P., McKay, R., Pollard, D., Ross, J., Winter, D., Barrett, P., Browne, G., Cody, R., Cowan, E., Crampton, J., Dunbar, G., Dunbar, N., Florindo, F., Gebbhardt, C., Graham, I., Hannah, M., Hansaraj, D., Harwood, D., Helling, D., Henrys, S., Hinnov, L., Kuhn, G., Kyle, P., Laufer, A., Maffioli, P., Magens, D., Mandernack, K., McIntosh, W., Millan, C., Morin, R., Ohneiser, C., Paulsen, T., Persico, D., Raine, I., Reed, J., Riesselman, C., Sagnotti, L., Schmitt, D., Sjunneskog, C., Strong, P., Taviani, M., Vogel, S., Wilch, T., and Williams, T. 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**: 322–328.

Sugden, D., Marchant, D., Potter, N., Souchez, R., Denton, G., Swisher, C., and Tison, J. 1995). Preservation of Miocene glacier ice in East Antarctica, *Nature* **376**: 412–414. doi:10.1038/376412a0.

5.8.3.2 Modern setting

Antarctica holds 91 percent of the world’s glacial ice, which is about 73 m of sea-level equivalent (Poore *et al.*, 2011), and its melting has the potential to cause major sea-level rise. Whether or not the Antarctic Ice Sheet is melting rapidly is therefore of great importance. News media carry stories nearly every week claiming the Antarctic ice sheet is melting at an accelerating rate and sea level will rise by up to 6 m in coming years. The imminent demise of the Antarctic Ice Cap was what Al Gore apparently had in mind when he warned, if “half of Antarctica melted or broke up and slipped into the sea, sea levels worldwide would increase by between 18 and 20 feet” (Gore 2006).

Ackert (2003) reported some scientists have indeed argued we are witnessing the CO₂-induced “early stages of rapid ice sheet collapse, with potential near-term impacts on the world’s coastlines.” But empirical evidence for such assertions is thin.

References

Ackert Jr., R.P. 2003. An ice sheet remembers. *Science* **299**: 57–58.

Gore, A. 2006. *An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It*. Rodale, Emmaus, PA, USA.

Poore, R.Z., Williams, R.S., and Tracey, C. 2000 (revised 2011). Sea level and climate. *United States Geological Survey (USGS) Fact Sheet* 002–00. <http://pubs.usgs.gov/fs/fs2-00/>.

Observations: The Cryosphere

5.8.3.3 Climatological reality

The average daily temperatures at the South Pole and Vostok, respectively, are -49.4°C (-57°F) and -55.1°C (-67.2°F). To melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0°C . This is not happening now, nor is it likely to happen. Claims of large-scale melting of the Antarctic ice sheet are highly exaggerated. The main Antarctic ice sheet has in fact been cooling since 1957 (see Figure 5.8.3.3.1) and ice accumulation is increasing there rather than decreasing.

The lack of a close network of weather stations in Antarctica makes interpretation of regional temperature distribution difficult. Steig *et al.* (2009) attempted to project temperatures from the West Antarctica Peninsula, where more data are available,

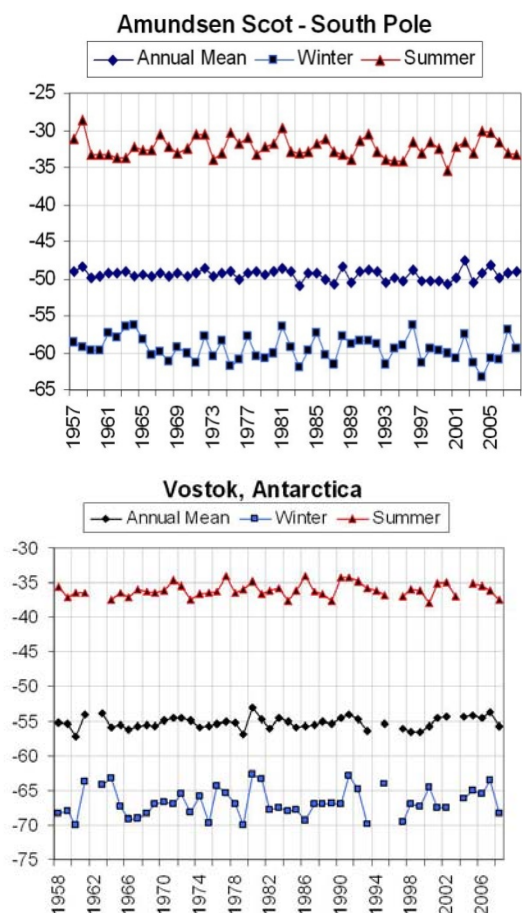


Figure 5.8.3.3.1. Temperature measurements at the South Pole (above) and Vostok (below). Note the lack of any indication of recent warming. Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

to the main Antarctic ice sheet and contended all of Antarctica was warming. That conclusion was hotly disputed by O'Donnell *et al.* (2010), who showed warming over the period of 1957–2006 was concentrated in the West Antarctic Peninsula and the main East Antarctic ice sheet was not warming (Figure 5.8.3.3.2).

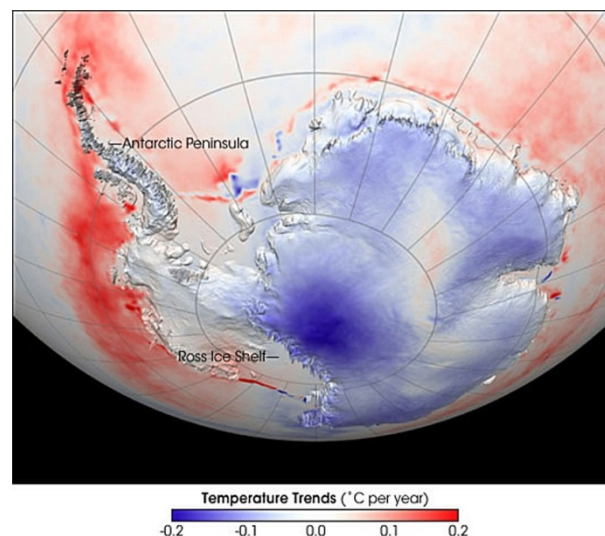


Figure 5.8.3.3.2. Rate of temperature trends in Antarctica between 1982 and 2004. Note almost all of the main East Antarctic Ice Sheet is cooling, not warming, and is not melting. The West Antarctic Peninsula is warmed by ocean currents (red). From National Oceanic and Atmospheric Administration, 2004. Antarctic temperature trend 1982–2004. <http://earthobservatory.nasa.gov/IOTD/view.php?id=6502>.

The West Antarctic Ice Sheet (WAIS) often has been described as the world's most unstable large ice sheet. As Hillenbrand *et al.* (2002) report, “it was speculated, from observed fast grounding-line retreat and thinning of a glacier in Pine Island Bay (Rignot, 1998; Shepherd *et al.*, 2001), from the timing of late Pleistocene-Holocene deglaciation in the Ross Sea (Bindschadler, 1998; Conway *et al.*, 1999), and from predicted activity of ice-stream drainage in response to presumed future global warming (Oppenheimer, 1998), that the WAIS may disappear in the future, causing the sea-level to rise at a rate of 1 to 10 mm/year (Bindschadler, 1998; Oppenheimer, 1998).”

References

Bindschadler, R. 1998. Future of the West Antarctic Ice Sheet. *Science* **282**: 428–429.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D. 1999. Past and future grounding-line retreat of the West Antarctic Ice Sheet. *Science* **286**: 280–283.

Easterbrook, D.J. (Ed.) 2011. Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming. Elsevier.

Hillenbrand, C-D., Futterer, D.K., Grobe, H., and Frederichs, T. 2002. No evidence for a Pleistocene collapse of the West Antarctic Ice Sheet from continental margin sediments recovered in the Amundsen Sea. *Geo-Marine Letters* **22**: 51–59.

National Oceanic and Atmospheric Administration, 2004. Antarctic temperature trend 1982–2004. <http://earthobservatory.nasa.gov/IOTD/view.php?id=6502>.

O'Donnell, R., Lewis, N., McIntyre, S., and Condon, J. 2011. Improved methods for PCA-based reconstructions: case study using the Steig et al. (2009) Antarctic temperature reconstruction. *Journal of Climate* **24**: 2099–2115.

Oppenheimer, M. 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature* **393**: 325–332.

Rignot, E.J. 1998. Fast recession of a West Antarctic glacier. *Science* **281**: 549–551.

Schoof, C. 2007. Ice sheet grounding line dynamics: Steady states, stability and hysteresis. *Journal of Geophysical Research* **112**: 10.1029/2006JF000664.

Shepherd, A., Wingham, D.J., Mansley, J.A.D., and Corr, H.F.J. 2001. Inland thinning of Pine Island Glacier, West Antarctica. *Science* **291**: 862–864.

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C., and Shindell, D.T. 2009: Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature* **457**: 459–462. doi:10.1038/nature07669.

5.8.3.4 Modelling studies and mass balance

Modelling studies have addressed how long it might take for extra warmth to bring about a collapse of the WAIS, with Pollard and DeConto (2009) concluding “the WAIS will begin to collapse when nearby ocean temperatures warm by roughly 5°C.” Huybrechts (2009) subsequently stated, “the amount of nearby ocean warming required to generate enough sub-ice-shelf melting to initiate a significant retreat of the West Antarctic ice sheet ... may well take several centuries to develop.” Once started, he concludes, the transition time for a total collapse of the West Antarctic Ice Sheet would range from “one thousand

to several thousand years.” This time period, Huybrechts notes, “is nowhere near the century timescales for West Antarctic ice-sheet decay based on simple marine ice-sheet models,” as often has been predicted in the past. Thus alarm about the short-term melting of significant volumes of the WAIS is unjustified.

Nevertheless, Gomez et al. (2010) report several studies (Oppenheimer, 1998; Meehl et al., 2007; Vaughan, 2008; Smith et al., 2009) whose authors have suggested “climate change could potentially destabilize marine ice sheets,² which would affect projections of future sea-level rise.” These studies highlight “an instability mechanism (Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007; Katz and Worster, 2010)” that “has been predicted for marine ice sheets such as the West Antarctic ice sheet that rest on reversed bed slopes, whereby ice-sheet thinning or rising sea levels leads to irreversible retreat of the grounding line.”

In contradiction of these fears, Gomez *et al.* present predictions of gravitationally self-consistent sea-level change modeled to follow grounding-line migration, derived by varying the initial ice-sheet size while considering the contribution to sea-level change that derives from various sub-regions of the simulated ice sheet. Their results “demonstrate that gravity and deformation-induced sea-level changes local to the grounding line contribute a stabilizing influence on ice sheets grounded on reversed bed slopes,” contrary to earlier assumptions. Rather than destabilizing the ice sheet, Gomez *et al.* concluded, “local sea-level change following rapid grounding-line migration will contribute a stabilizing influence on marine ice sheets, even when grounded on beds of non-negligible reversed slopes.”

Zwally and Giovinetto (2011) have provided a thorough review of the differing mass balance estimates for the Antarctic Ice Sheet (AIS) provided in earlier papers and by the IPCC. For the period 1992–2009, they report, estimates of annual mass change fall between values of +50 and -250 Gt/year. This 300 Gt/year range represents about 15 percent of the annual mass input to the AIS, and about 0.8 mm/year sea-level equivalent (SLE). They further note two estimates (+28 and -31 Gt/year) from radar altimeter measurements made by European Remote-sensing Satellites (ERS) lie in the upper part of the

² The term “marine ice sheet” appears to refer to icecaps, such as those of Greenland and Antarctica, that are surrounded by and therefore debouch into the ocean.

Observations: The Cryosphere

range, whereas estimates from the Input-minus-Output Method (IOM) and Gravity Recovery and Climate Experiment (GRACE) lie in the lower part (-40 to -246 Gt/year) of the range. By using an alternative method to process the IOM-GRACE data, Zwally and Giovinetto found “the modified IOM and a GRACE-based estimate for observations within 1992–2005 lie in a narrowed range of +27 to -40 Gt/year, which is about 3% of the annual mass input and only 0.2 mm/year SLE.”

Zwally and Giovinetto say their preferred estimate for Antarctic mass balance changes for 1992–2001 is -47 Gt/year for West Antarctica, +16 Gt/year for East Antarctica, and -31 Gt/year overall. They expressly report their results do not support the large and increasing rates of mass loss predicted in GRACE-based studies. The potential for large errors to occur in GRACE-based studies, which typically suggest overly large ice losses, has previously been stressed by Ramillien *et al.* (2006), Velicogna and Whar (2006), and Quinn and Ponte (2010). This makes it likely the Zwally and Giovinetto conclusion of a small annual Antarctic ice loss of -31 Gt/year (about 0.1 mm/yr SLE) is probably as accurate a result as it is currently possible to achieve.

Frezzotti *et al.* (2013) present a detailed analysis of the surface mass balance anomaly (SMB) for Antarctica derived from ice core data. An SMB is a step toward accomplishing a full mass balance, and it is usually defined as the difference at any location between accumulation from solid precipitation (snow) and mass loss from ablation and wind erosion. The total SMB of the grounded AIS is about 2,100 Gt/yr, with a large interannual variability up to 300 Gt/yr (Van den Broeke *et al.*, 2011).

Frezzotti *et al.* show the Antarctic SMB over the past 50 years is not unusual compared with the previous 750 years and falls well within the level of prior natural variations between <50 and >700 kg/m²/yr. They also demonstrate a good correlation exists between temporal variations in SMB and solar activity on the scale of the 200-year de Vries cycle. Beyond these studies, the preparation of the required full mass balance budget for an ice sheet requires accounting for Dynamic Ice Loss (DIL) as well as SMB; DIL, which represents the breakup and melting of the terminus of peripheral or valley outlet glaciers, is a difficult number to estimate accurately (Magand *et al.* 2007; Frezzotti *et al.*, 2007).

Boening *et al.* (2012) point out “an improved understanding of processes dominating the sensitive balance between mass loss primarily due to glacial discharge and mass gain through precipitation is

essential for determining the future behavior of the Antarctic ice sheet and its contribution to sea level rise.” They set out to assess the causes and magnitude of recent (2009–2011) extreme precipitation events along the East Antarctic coast, using data derived from CloudSat and ERA Interim reanalysis products (Dee *et al.*, 2011).

They found regional mass gain occurred mainly during May 2009 and June 2011, with most of the accumulation occurring in only a few main snowfalls driven by “prolonged changes in pressure patterns and induced poleward wind in the two years.” Over the same period, and consistent with their precipitation analysis, GRACE satellite measurements indicate an abrupt mass increase of almost 350 Gt from 2009 to 2011 in East Antarctica along the coast of Dronning Maud Land. This mass increase is equivalent to a decrease in global mean sea level at a rate of 0.32 mm/year.

Putting these results into a longer-term context, Boening *et al.* report the ERA Interim reanalysis data show no significant change in snowfall frequency or strength between 1979 and 2008. Comparing this decadal-scale stability with their finding of abrupt and episodic mass increase in 2009 and 2011, it is apparent stochastic precipitation events can affect regional mass balance in ways that significantly slow the rate of global sea-level rise.

References

- Boening, C., Lebsack, M., Landerer, F., and Stephens, G. 2012. Snowfall-driven mass change on the East Antarctic ice sheet. *Geophysical Research Letters* **39**: 10.1029/2012GL053316.
- Dee, D.P. *et al.* 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**: 553–597.
- Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., and Urbini S. 2013. A synthesis of the Antarctic surface mass balance during the last 800 yr. *The Cryosphere* **7**: 303–319. doi:10.5194/tc-7-303-2013.
- Frezzotti, M., Urbini, S., Proposito, M., Scarchilli, C., and Gandolfi, S. 2007. Spatial and temporal variability of surface mass balance near Talos Dome, East Antarctica. *Journal of Geophysical Research* **112**: F02032. doi:10.1029/2006JF000638.
- Gomez, N., Mitrovica, J.X., Huybers, P., and Clark, P.U. 2010. Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nature Geoscience* **3**: 850–853.

Huybrechts, P. 2009. West-side story of Antarctic ice. *Nature* **458**: 295–296.

Katz, R.F. and Worster, M.G. 2010. Stability of ice-sheet grounding lines. *Proceedings of the Royal Society A* **466**: 1597–1620.

Magand, O., Genthon, C., Fily, M., Krinner, G., Picard, G., Frezzotti, M., and Ekaykin, A. A. 2007. An up-to-date quality-controlled surface mass balance data set for the 90°–180° E Antarctica sector and 1950–2005 period. *Journal of Geophysical Research* **112**: D12106. doi:10.1029/2006JD007691.

Meehl, G.A. and Stocker, G.F. 2007. In: *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S. et al. (Eds.), pp. 748–845. Cambridge University Press, Cambridge, U.K.

Oppenheimer, M. 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature* **393**: 325–332.

Pollard, D. and DeConto, R.M. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**: 329–332.

Quinn, K.J. and Ponte, R.M. 2010. Uncertainty in ocean mass trends from GRACE. *Geophysical Journal International* **181**: 762–768.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R. 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change* **53**: 198208.

Schoof, C. 2007. Ice sheet grounding line dynamics: Steady states, stability and hysteresis. *Journal of Geophysical Research* **112**: 10.1029/2006JF000664.

Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Fussel, H.-M., Pittock, A.B., Rahman, A., Suarez, A., and van Ypersele, J.-P. 2009. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC), ‘Reasons for Concern’. *Proceedings of the National Academy of Sciences, USA* **106**: 4133–4137.

Thomas, R.H. and Bentley, C.R. 1978. A model for Holocene retreat of the West Antarctic ice sheet. *Quaternary Research* **10**: 150–170.

van den Broeke, M.R., Bamber, J., Lenaerts, J., and Rignot, E. 2011. Ice sheet and sea level: thinking outside the box. *Surveys in Geophysics* **32**: 495–505. doi:10.1007/s10712-011-9137-z, 2011.

Vaughan, D.G. 2008. West Antarctic Ice Sheet collapse—the fall and rise of a paradigm. *Climatic Change* **91**: 65–79.

Velicogna, I. and Wahr, J. 2006. Measurements of time-variable gravity show mass loss in Antarctica. *Science* **311**: 1754–1756.

Weertman, J. 1974. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology* **13**: 3–11.

Zwally, H.J. and Giovinetto, M.B. 2011. Overview and assessment of Antarctic Ice-Sheet mass balance estimates: 1992–2009. *Surveys in Geophysics* **32**: 351–376.

Earlier research

Other research regarding the stability and natural variation of the WAIS and EAIS is described and discussed in the following papers.

- Bell *et al.* (1998) used airborne geophysical data to study fast-moving ice streams on the WAIS. In conjunction with models, their data suggested a close correlation between the margins of various ice streams and the underlying configuration of sedimentary basins, which in parts appear to act as lubricants for the overlying ice. They conclude, “geological structures beneath the West Antarctic Ice Sheet have the potential to dictate the evolution of the dynamic ice system, modulating the influence of changes in the global climate system,” though without indicating how such modulation might work.
- In a review of the WAIS, Bindshadler (1998) analyzed the historical retreat of its grounding line and ice front. Since the Last Glacial Maximum, the retreat of the grounding line occurred faster than its ice front, resulting in an expanding Ross Ice Shelf. Bindshadler reports “the ice front now appears to be nearly stable,” although its grounding line may be retreating at a slow rate that would cause dissipation of the WAIS in about 4,000–7,000 years time. Such a retreat, if it occurs, would sustain a sea-level rise of 0.8–1.3 mm/year. Even the slowest of these rates of sea-level rise would require a large negative mass balance for all of West Antarctica, which is not apparent in available data.
- Bindshadler and Vornberger (1998) utilized the available satellite imagery to examine changes of EAIS Ice Stream B, which flows into the Ross Ice Shelf. Since 1963, the ice stream’s width has increased by nearly 4 kilometers, at a rate an “order of magnitude faster than models have predicted.” However, the authors also report the flow speed of the ice stream decreased over this time period by about 50 percent, noting “such high rates of change in velocity greatly complicate the calculation of mass balance of the ice sheet.”
- Oppenheimer (1998) reported on 122 studies

Observations: The Cryosphere

concerned with the stability of the WAIS and its effects on global sea level. He concludes, “human-induced climate change may play a significant role in controlling the long-term stability of the West Antarctic Ice Sheet and in determining its contribution to sea-level change in the near future.” Interestingly, however, specific studies Oppenheimer cites provide quite contrary evidence or conclusions. For example, he reports the IPCC “estimated a zero Antarctic contribution to sea-level rise over the past century, and projected a small negative (about -1 cm) contribution for the twenty-first century” and regarding sea-ice extent “the IPCC assessment is that no trend has yet emerged.” Regarding the state and behavior of the Antarctic atmosphere and ocean, he also acknowledges “measurements are too sparse to enable the observed changes to be attributed to any such [human-induced] global warming.”

Oppenheimer concludes his review with four future scenarios for the WAIS based upon differing assumptions: (1) that the WAIS will collapse suddenly and cause a 4–6 m sea-level rise within the coming century; (2) that the WAIS will gradually disintegrate, with slow sea-level rise over the next two centuries and more rapid disintegration and sea-level rise over the following 200 years; (3) that the WAIS melts over 500–700 years, raising sea level by 6–12 mm/year; and (4) that instead of disintegrating, ice streams slow and the discharge of grounded ice decreases, leading to intra-ice sheet accretion and falling sea level. These scenarios all remain speculative, as Oppenheimer comments, “it is not possible to place high confidence in any specific prediction about the future of WAIS.”

- Wingham *et al.* (1998) studied the combined East and West Antarctic ice sheets using satellite radar altimeter measurements from 1992 to 1996 to estimate their rate of change of thickness, and using snowfall variability data from ice cores to calculate a mass balance for the Antarctic ice sheet over the past century. They conclude “a large century-scale imbalance for the Antarctic interior is unlikely,” not least because of relative sea level and geodetic evidence suggesting “the grounded ice has been in balance at the millennial scale.”
- Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of sediment cores from the eastern Weddell Sea continental shelf and nearby deep-sea floor in an attempt to track the behavior of the East and West Antarctic ice sheets. They found “significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum,” and the ice masses around the

Weddell Sea today “are more extensive than they were during the previous glacial minimum.” They conclude “the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and ... the modern West and East Antarctic ice sheets have not yet shrunk to their minimum.”

- Conway *et al.* (1999) examined the retreat of the WAIS since its maximum glacial extent 20,000 years ago. They determined the ice grounding line remained near its maximum until about 10,000 years ago, after which it retreated at a rate of about 120 meters per year, this rate also characterizing late twentieth century retreat. The researchers conclude the modern retreat of the WAIS is part of an ongoing recession underway since the early Holocene, and “it is not a consequence of anthropogenic warming or recent sea-level rise.” Extrapolating the Holocene retreat rate into the future, a complete and natural deglaciation of the WAIS will occur by about 7,000 years hence.
- Cofaigh *et al.* (2001) analyzed sediment cores from west of the Antarctic Peninsula and the Weddell and Scotia Seas for ice-rafted debris (IRD), seeking an Antarctic analogue of the Heinrich layers of the North Atlantic Ocean, which testify to the repeated collapse of the eastern Laurentide Ice Sheet and discharge of icebergs. Their search was in vain, and the rarity of IRD layers they found “argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles.”
- Pudsey and Evans (2001) studied ice-rafted debris obtained from four cores in Prince Gustav Channel, which until 1995 was covered by a floating ice shelf. Their results indicate a retreat of the ice shelf had occurred in the mid-Holocene, since when “colder conditions after about 1.9 ka allowed the ice shelf to reform.” In light of this evidence for preindustrial natural change, Pudsey and Evans were careful to state, “we should not view the recent [ice] decay as an unequivocal indicator of anthropogenic climate change.” It is likely the breakup of the Prince Gustav Channel ice shelf marks only the culmination of the Antarctic Peninsula’s natural recovery from the Little Ice Age.
- Shepherd *et al.* (2001) used satellite altimetry and interferometry to measure the rate of change of the ice thickness of the Pine Island Glacier drainage basin, WAIS, between 1992 and 1999. The grounded glacier thinned at a constant rate of 1.6 m/year, and this “thinning cannot be explained by short-term variability in accumulation and must result from

glacier dynamics.” Because glacier dynamics typically respond to phenomena operating on time scales of hundreds to thousands of years, this observation argues against twentieth century warming being a primary cause of the thinning; instead, a long-term phenomenon of considerable inertia must be at work in this particular situation.

- Hillenbrand *et al.* (2002) undertook studies of sediment cores from the Amundsen Sea, West Antarctica, a site likely to be sensitive to environmental changes related to WAIS collapse. They found all proxies sensitive to collapse changed markedly during the global climatic cycles of the past 1.8 million years, but at no level was evidence found for a Pleistocene disintegration of the WAIS. The authors remark their results “suggest relative stability rather than instability of the WAIS during the Pleistocene climatic cycles,” a conclusion “consistent with only a minor reduction of the WAIS during the last [warmer] interglacial period.” A similar conclusion was reached by Huybrechts (1990), Cuffey and Marshall (2000), and Huybrechts (2002).

- In another paper addressing possible WAIS collapse, O'Neill and Oppenheimer (2002) speculate the ice sheet “may have disintegrated in the past during periods only modestly warmer ($\sim 2^{\circ}\text{C}$ global mean) than today,” thereby claiming that setting “a limit of 2°C above the 1990 global average temperature”—above which the mean temperature of the globe should not be allowed to rise—is justified.” We are aware of no empirical evidence to support this claim.

- Raymond (2002) presents a brief appraisal of the status of the world's major ice sheets. Relative to the WAIS, he concludes “substantial melting on the upper surface of WAIS would occur only with considerable atmospheric warming.” In a summary statement taking account of the available observations, Raymond writes “the total mass of today's ice sheets is changing only slowly, and even with climate warming increases in snowfall should compensate for additional melting,” such as might occur for the WAIS if the planet's temperature should resume its post-Little Ice Age warming.

- Stone *et al.* (2003) used cosmogenic ^{10}Be exposure dates of glacially transported cobbles in elevation transects on the Ford Ranges, western Marie Byrd Land, to reconstruct a history of ice-sheet thinning over the past 10,000-plus years. They conclude “the exposed rock in the Ford Ranges, up to 700 m above the present ice surface, was deglaciated within the past 11,000 years,” and evidence also

suggests the maximum ice sheet stood considerably higher than this. Comparing the age of exposure with site elevation “indicates steady deglaciation since the first of these peaks emerged from the ice sheet some time before 10,400 years ago” and demonstrates the mass balance of the region has been negative throughout the Holocene. They conclude it is clear that West Antarctic deglaciation continued long after the disappearance of the Northern Hemisphere ice sheets, and may still be under way.

- Davis and Ferguson (2004) evaluated elevation changes of the Antarctic ice sheet for 1995–2000, measured by radar altimetry from the European Space Agency's European Remote Sensing 2 satellite. They found the East Antarctic Ice Sheet had a five-year trend of 1.0 ± 0.6 cm/year, the West Antarctic Ice Sheet a five-year trend of -3.6 ± 1.0 cm/year, and the entire Antarctic continent a five-year trend of 0.4 ± 0.4 cm/year. Melting was apparent in the Pine Island, Thwaites, DeVicq, and Land glaciers of West Antarctica, which exhibited five-year trends ranging from -26 to -135 cm/year, and this was interpreted as resulting from stronger glacial flow caused by warm ocean temperatures having enhanced basal melting.

- In 2005, the journal *Climatic Change* published an editorial essay by Oppenheimer and Alley, who discussed “the degree to which warming (of the Antarctic and Greenland ice sheets) can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other.” In their opinion, the key questions with respect to both ice sheets were “What processes limit ice velocity, and how much can warming affect those processes?” Commenting that no scientific consensus exists on the answers, they identify 14 areas in which our knowledge of the matter remains uncertain (Table 1), reflecting both the weakness of current models and the uncertainty in paleoclimatic reconstructions. Oppenheimer and Alley identify this list of deficiencies of knowledge as “gaping holes in our understanding.”

- Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the period 2002–2005. They conclude “the ice sheet mass decreased significantly, at a rate of 152 ± 80 km³/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea-level rise.” The mass loss came entirely from the WAIS; the East Antarctic Ice Sheet mass balance was 0 ± 56 km³/year. Velicogna and Wahr

Observations: The Cryosphere

- concede there is both ambiguity and geophysical contamination caused by signals from outside Antarctica, including continental hydrology and ocean mass variability. The GRACE mass solutions “do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years).” These estimates and adjustments are convoluted and complex, as well as highly dependent upon various models. Velicogna and Wahr acknowledge “the PGR contribution is much larger than the uncorrected GRACE trend” (by a factor of almost five), and “a significant ice mass trend does not appear until the PGR contribution is removed.” Clearly these results apply to too short a period of time, and are too model-dependent, to be useful.

- van de Berg *et al.* (2006) compared results of model-simulated Antarctic surface mass balance (SMB) and all available mass balance observations to construct “a best estimate of contemporary Antarctic SMB.” SMB data was derived from Vaughan *et al.* (1999), van den Broeke *et al.* (1999), Frezzotti *et al.* (2004), Karlof *et al.* (2000), Kaspari *et al.* (2004), Magand *et al.* (2004), Oerter *et al.* (1999, 2000), Smith *et al.* (2002), and Turner *et al.* (2002). The measurements included moving surficial stake arrays, location of atom bomb geochemical tracer horizons, and chemical analyses of ice cores.

van de Berg *et al.* determined “the SMB integrated over the grounded ice sheet (171 ± 3 mm per year) exceeds previous estimates by as much as 15%.” Their results differ by more than a meter per year higher in coastal areas of both East and West Antarctica.

- In another altimeter study, Wingham *et al.* (2006) utilized European remote sensing satellite measurements to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. Their measurements covered 72 percent of the area of the grounded ice sheet. After correction for isostatic rebound, these authors found the ice sheet to be growing at 5 ± 1 mm per year. This translates to the ice sheet gaining 27 ± 29 Gt of ice per year, which would lower global sea level by 0.08 mm per year.

- Ramillien *et al.* (2006) provided new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period 2002–2005, identifying a mass loss of 107 ± 23 km³/year for West Antarctica and a gain of 67 ± 28 km³/year for East

Table 1.
Summary Points from the
Oppenheimer and Alley (2005) review

Regarding the Antarctic and Greenland ice sheets, we do not know:

- i. If the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) could occur more generally over the ice sheets.
- ii. If dynamical responses are likely to continue for centuries and propagate further inland, or if it is more likely they will be damped over time.
- iii. If surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.
- iv. If ice sheets made a significant net contribution to sea-level rise over the past several decades.
- v. What might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.
- vi. The reliability of Antarctic and Southern Ocean temperatures (and polar amplification) projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.
- vii. The prospects for expanding measurements and improving models of ice sheets, nor the timescales involved.
- viii. If current uncertainties in future ice sheet behavior can be expressed quantitatively.
- ix. What would be useful early warning signs of impending ice-sheet disintegration nor when these might be detectable.
- x. Given current uncertainties, if our present understanding of the vulnerability of either the WAIS or GIS is potentially useful in defining “dangerous anthropogenic interference” with Earth’s climate system.
- xi. If the concept of a threshold temperature is useful.
- xii. If either ice sheet seems more vulnerable, and thus should provide a more immediate measure of climate “danger” and a more pressing target for research.
- xiii. If any of the various temperatures proposed in the literature as demarcating danger of disintegration for one or the other ice sheet is useful in contributing to a better understanding of “dangerous anthropogenic interference.”
- xiv. On what timescale future learning might yield the answers to these questions.

- Antarctica, resulting in an average net ice loss for the entire continent of 40 km³/year and a sea-level rise of 0.11 mm/year. This result is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea-level rise calculated by Zwally *et al.* (2005), which was derived from nine years of satellite radar altimetry data from the European Remote-sensing Satellites ERS-1 and -2. However, and as Ramillien *et al.* concede, “the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations.”
- Remy and Frezzotti (2006) review the three principal ways by which ice sheet mass balance is estimated: by measuring the difference between mass input and output, by monitoring the changing geometry of the continent, and by modeling the dynamic and climatic evolution of the continent. The researchers conclude “the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance.” They also report “the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale,” which they describe in terms of centuries.
- Van den Broeke *et al.* (2006) employed a regional atmospheric climate model (RACMO2), with snowdrift-related processes calculated offline, to calculate the flux of solid precipitation (Ps), surface sublimation (SU), sublimation from suspended (drifting/saltating) snow particles, horizontal snow drift transport, and surface melt (ME). Having found a good match between the model output and observations, and after analyzing the data-driven results for trends over the period 1980–2004, the researchers report “no trend is found in any of the Antarctic SSMB components, nor in the size of ablation areas.”
- Krinner *et al.* (2007) used the LMDZ4 atmospheric general circulation model (Hourdin *et al.*, 2006) to simulate Antarctic climate for the periods 1981–2000, to test the model’s ability to adequately simulate present conditions, and 2081–2100, to see what the future might hold. They conclude “the simulated present-day surface mass balance is skilful on continental scales,” which gives them confidence regarding their mass balance projections for the end of the twenty-first century.

The projections indicate by that time “the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year,” which corresponds to a sea-level decrease of 1.2 mm per year by the end of the century and a cumulative sea-level decrease of about 6 cm. The simulated temperature increase causes increased moisture transport toward the interior of the continent where the moisture falls as snow, causing the continent’s ice sheet to grow.

Conclusions

Several arguments contradict the idea that human-caused global warming is putting Antarctica under threat of massive ice loss with attendant effects on local environments and global sea-level rise.

First, the mild warming witnessed in the late twentieth century was well within the bounds of natural variation and now has ceased: Global average temperature has not increased since at least 1996. The warming that is assumed to drive the system, and in particular all of the model studies, is no longer occurring.

Second, and even if warming were still occurring, the results of Krinner *et al.* (2007) suggest the likely regional response is enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; i.e., an increasingly positive mass balance.

Third, despite the last few interglacials being warmer than the Holocene by 2–5° C (Petit *et al.*, 1999), several studies have found sediment cores adjacent to Antarctica provide no evidence of any dramatic breakups of the WAIS over the past few glacial cycles. With or without resumed global warming, there is therefore no reason to expect changes in the Antarctic icecap other than those that happen naturally. Furthermore, we know throughout the long central portion of the current interglacial when the most recent peak Antarctic temperature was reached, it was much warmer than it was in the late twentieth century, yet no evidence exists of even a partial WAIS disintegration at that time. The Antarctic ice sheet also appears to have been impervious to the effects of the climate change that characterized the Medieval Warm Period and Little Ice Age. Representing, as they do, the 1,500-yr Bond rhythm, these types of events—and specifically, a new Little Ice Age—are the most likely significant external major forcing agents that will confront Antarctica over the next 1,000 years.

Fourth, though most mass balance calculations are based upon the shifting sands of computer modeling, the evidence so far indicates West

Observations: The Cryosphere

Antarctica is warming and losing significant ice mass, and East Antarctica is cooling and accreting ice. The sum of that evidence indicates the whole Antarctic icecap is close to mass balance (Zwally and Giovenetto, 2011). As Davis and Ferguson (2004) have shown, and driven by the significantly positive trend of the much larger East Antarctic ice sheet, the ice volume of Antarctica increased over the last five years of the twentieth century, driven by increased snowfall.

Fifth, many of the most cited papers on Antarctica involve complex computer modeling and applying the GRACE gravity data and a contemporary geoid model, both of which are highly uncertain. The modeling study of Krinner *et al.* (2007) demonstrated an impressive ability to reconstruct past mass balance changes over the late twentieth century and may therefore perhaps be viewed with a little more confidence than most other similar studies. The projections of this model out to 2100, and based upon continuing warming, are for increased ice accretion across Antarctica. Thus, at least one successful model predicts CO₂-induced global warming, should it occur, will actually buffer the world against the much-hypothesized catastrophic loss of ice mass from the polar icecaps and also against the feared impact of ice-melt-driven sea-level rise.

Sixth, and finally, several studies, for example from Marie Byrd Land and in Pine Island Bay, have demonstrated a pattern of steady Holocene ice retreat that occurred at rates similar to modern retreat. The authors of these studies have concluded this retreat is simply a manifestation of the slow but steady deglaciation taking place ever since end of the last great ice age. As Ackert (2003) states, “recent ice sheet dynamics appear to be dominated by the ongoing response to deglacial forcing thousands of years ago, rather than by a recent anthropogenic warming or sea-level rise.” Therefore, and as Anderson and Andrews (1999) have shown, the great inertial forces at work over the millennia suggest parts of the East and West Antarctic Ice Sheets will continue to slowly wane and release icebergs to the Southern Ocean over the coming years, decades, and centuries quite independent of short-term changes in global air temperature.

References

- Ackert Jr., R.P. 2003. An ice sheet remembers. *Science* **299**: 57–58.
- Anderson, J.B. and Andrews, J.T. 1999. Radiocarbon constraints on ice sheet advance and retreat in the Weddell Sea, Antarctica. *Geology* **27**: 179–182.
- Bell, R.E., Blankenship, D.D., Finn, C.A., Morse, D.L., Scambos, T.A., Brozena, J.M., and Hodge, S.M. 1998. Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations. *Nature* **394**: 58–62.
- Bindschadler, R. 1998. Future of the West Antarctic Ice Sheet. *Science* **282**: 428–429.
- Bindschadler, R. and Vornberger, P. 1998. Changes in the West Antarctic Ice Sheet since 1963 from declassified satellite photography. *Science* **279**: 689–692.
- Cofaigh, C.O., Dowdeswell, J.A., and Pudsey, C.J. 2001. Late Quaternary iceberg rafting along the Antarctic Peninsula continental rise in the Weddell and Scotia Seas. *Quaternary Research* **56**: 308–321.
- Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D. 1999. Past and future grounding-line retreat of the West Antarctic Ice Sheet. *Science* **286**: 280–283.
- Cuffey, K.M. and Marshall, S.J. 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature* **404**: 591–594.
- Davis, C.H. and Ferguson, A.C. 2004. Elevation change of the Antarctic ice sheet, 1995–2000, from ERS-2 satellite radar altimetry. *IEEE Transactions on Geoscience and Remote Sensing* **42**: 2437–2445.
- Dufresne, J.L., Quaas, J., Boucher, O., Denvil, S., and Fairhead, L. 2005. Contrasts in the effects on climate of anthropogenic sulfate aerosols between the 20th and the 21st century. *Geophysical Research Letters* **32**: 10.1029/2005GL023619.
- Frezzotti, M., Pourchet, M., Flora, O., Gandolfi, S., Gay, M., Urbini, S., Vincent, C., Becagli, S., Gragnani, R., Proposito, M., Severi, M., Traversi, R., Udisti, R., and Fily, M. 2004. New estimations of precipitation and surface sublimation in East Antarctica from snow accumulation measurements. *Climate Dynamics* **23**: 803–813.
- Hillenbrand, C-D., Futterer, D.K., Grobe, H., and Frederichs, T. 2002. No evidence for a Pleistocene collapse of the West Antarctic Ice Sheet from continental margin sediments recovered in the Amundsen Sea. *Geo-Marine Letters* **22**: 51–59.
- Hourdin, F., Musat, I., Bony, S., Braconnot, P., Codron, F., Dufresne, J.L., Fairhead, L., Filiberti, M.A., Friedlingstein, P., Grandpeix, J.Y., Krinner, G., Le Van, P., Li, Z.X., and Lott, F. 2006. The LMDZ4 general circulation model: climate performance and sensitivity to parameterized physics with emphasis on tropical convection. *Climate Dynamics* **27**: 787–813.

- Huybrechts, P. 2002. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. *Quaternary Science Reviews* **21**: 203–231.
- Huybrechts, P. 2009. West-side story of Antarctic ice. *Nature* **458**: 295–296.
- Karlof, L., Winther, J.-G., Isaksson, E., Kohler, J., Pinglot, J.F., Wilhelms, F., Hansson, M., Holmlund, P., Nyman, M., Pettersson, R., Stenberg, M., Thomassen, M.P.A., van der Veen, C., and van de Wal, R.S.W. 2000. A 1500-year record of accumulation at Amundsenisen western Dronning Maud Land, Antarctica, derived from electrical and radioactive measurements on a 120-m ice core. *Journal of Geophysical Research* **105**: 12,471–12,483.
- Kaspari, S., Mayewski, P.A., Dixon, D.A., Spikes, V.B., Sneed, S.B., Handley, M.J., and Hamilton, G.S. 2004. Climate variability in West Antarctica derived from annual accumulation rate records from ITASE firn/ice cores. *Annals of Glaciology* **39**: 585–594.
- Krinner, G., Magand, O., Simmonds, I., Genthon, C., and Dufresne, J.L. 2007. Simulated Antarctic precipitation and surface mass balance at the end of the twentieth and twenty-first centuries. *Climate Dynamics* **28**: 215–230.
- Magand, O., Frezzotti, M., Pourchet, M., Stenni, B., Genoni, L., and Fily, M. 2004. Climate variability along latitudinal and longitudinal transects in East Antarctica. *Annals of Glaciology* **39**: 351–358.
- Marti, O., Braconnot, P., Bellier, J., Benshila, R., Bony, S., Brockmann, P., Cadule, P., Caubel, A., Denvil, S., Dufresne, J.L., Fairhead, L., Filiberti, M.A., Foujols, M.A., Fichefet, T., Friedlingstein, P., Grandpeix, J.Y., Hourdin, F., Krinner, G., Levy, C., Madec, G., Musat, I., de Noblet-Ducoudre, N., Polcher, J., and Talandier, C. 2005. The new IPSL climate system model: IPSL-CM4. *Note du Pole de Modelisation* **6**, IPSL, ISSN 1288–1619.
- Oerter, H., Graf, W., Wilhelms, F., Minikin, A., and Miller, H. 1999. Accumulation studies on Amundsenisen, Dronning Maud Land, by means of tritium, dielectric profiling and stable-isotope measurements: First results from the 1995–96 and 1996–97 field seasons. *Annals of Glaciology* **29**: 1–9.
- Oerter, H., Wilhelms, F., Jung-Rothenhausler, F., Goktas, F., Miller, H., Graf, W., and Sommer, S. 2000. Accumulation rates in Dronning Maud Land, Antarctica, as revealed by dielectric-profiling measurements of shallow firn cores. *Annals of Glaciology* **30**: 27–34.
- O'Neill, B.C. and Oppenheimer, M. 2002. Dangerous climate impacts and the Kyoto Protocol. *Science* **296**: 1971–1972.
- Oppenheimer, M. 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature* **393**: 325–332.
- Oppenheimer, M. and Alley, R.B. 2005. Ice sheets, global warming, and article 2 of the UNFCCC. *Climatic Change* **68**: 257–267.
- Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.
- Pudsey, C.J. and Evans, J. 2001. First survey of Antarctic sub-ice shelf sediments reveals mid-Holocene ice shelf retreat. *Geology* **29**: 787–790.
- Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R. 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change* **53**: 198–208.
- Raymond, C.F. 2002. Ice sheets on the move. *Science* **298**: 2147–2148.
- Remy, F. and Frezzotti, M. 2006. Antarctica ice sheet mass balance. *Comptes Rendus Geoscience* **338**: 1084–1097.
- Shepherd, A., Wingham, D.J., Mansley, J.A.D., and Corr, H.F.J. 2001. Inland thinning of Pine Island Glacier, West Antarctica. *Science* **291**: 862–864.
- Smith, B.T., van Ommen, T.D., and Morgan, V.I. 2002. Distribution of oxygen isotope ratios and snow accumulation rates in Wilhelm II Land, East Antarctica. *Annals of Glaciology* **35**: 107–110.
- Stone, J.O., Balco, G.A., Sugden, D.E., Caffee, M.W., Sass III, L.C., Cowdery, S.G., and Siddoway, C. 2003. Holocene deglaciation of Marie Byrd Land, West Antarctica. *Science* **299**: 99–102.
- Turner, J., Lachlan-Cope, T.A., Marshall, G.J., Morris, E.M., Mulvaney, R., and Winter, W. 2002. Spatial variability of Antarctic Peninsula net surface mass balance. *Journal of Geophysical Research* **107**: 10.1029/JD000755.
- Van de Berg, W.J., van den Broeke, M.R., Reijmer, C.H., and van Meijgaard, E. 2006. Reassessment of the Antarctic surface mass balance using calibrated output of a regional atmospheric climate model. *Journal of Geophysical Research* **111**: 10.1029/2005JD006495.
- Van den Broeke, M., van de Berg, W.J., van Meijgaard, E., and Reijmer, C. 2006. Identification of Antarctic ablation areas using a regional atmospheric climate model. *Journal of Geophysical Research* **111**: 10.1029/2006JD007127.
- Vaughan, D.G., Bamber, J.L., Giovinetto, M., Russell, J., and Cooper, A.P.R. 1999. Reassessment of net surface mass balance in Antarctica. *Journal of Climate* **12**: 933–946.

Observations: The Cryosphere

Velicogna, I. and Wahr, J. 2006. Measurements of time-variable gravity show mass loss in Antarctica. *Scienceexpress* 10.1126 science.1123785.

Wingham, D.J., Ridout, A.J., Scharroo, R., Arthern, R.J., and Shum, C.K. 1998. Antarctic elevation change from 1992 to 1996. *Science* **282**: 456–458.

Wingham, D.J., Shepherd, A., Muir, A., and Marshall, G.J. 2006. Mass balance of the Antarctic ice sheet. *Philosophical Transactions of the Royal Society A* **364**: 1627–1635.

Zwally, H.J. and Giovinetto, M.B. 2011. Overview and assessment of Antarctic Ice-Sheet mass balance estimates: 1992–2009. *Surveys in Geophysics* **32**: 351–376.

Zwally, H.J., Giovinetto, M.B., Li, J., Cornejo, H.G., Beckley, M.A., Brenner, A.C., Saba, J.L., and Yi, D. 2005. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *Journal of Glaciology* **51**: 509–527.

5.8.4 Stability of the Greenland Ice Sheet

The Greenland ice sheet is the second largest ice mass in the world (Figure 5.8.4.1). It is 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km². The mean altitude of the ice surface is 2,135 m, and the ice is up nearly 3 km thick in central Greenland. The lowest mean annual temperatures are about -31°C. Because the Greenland ice sheet is not a polar glacier, meltwater occurs at the base of the glacier, which facilitates basal sliding. The ice sheet margin reaches the sea only in limited areas, so no large ice shelves occur. Large outlet glaciers flow through deep fiords around the periphery of

Greenland and calve off into the ocean, producing numerous icebergs.

Many claims are made that melting of the Greenland ice sheet during the post-1977 warm period occurred at an unprecedented or extreme rate, and that in consequence damaging sea-level rise would occur. These claims seldom are tested against known climatic records. Past temperature records (Figure 5.8.4.2) show Greenland has followed a predictable pattern of multidecadal warming and cooling over the past century. Ice volume also has waxed and waned, following both global temperatures and the warming/cooling patterns in the oceans (Chylek *et al.*, 2004, 2006). Greenland's history includes two periods of cooling and two periods of warming over the past 100 years, with the warmest year being 1941 and the warmest decades being the 1930s and 1940s.

The most recent (post-1977) Arctic warming and resultant increased ice melt were not at all unusual. Kobashi *et al.* (2011) provide a longer, 2,000-year long context for these historical measurements (Figure 5.8.4.3). They reconstructed Greenland surface snow temperature variability at the GISP2 site using argon and nitrogen isotopic ratios ($\delta^{15}\text{N}$, $\delta^{40}\text{Ar}$) from air bubbles in the core, finding the average Greenland snow temperature over the past 4,000 years has been -30.7°C with a standard deviation of 1.0°C. In comparison, the current decadal average surface temperature (2001–2010) at the GISP2 site is -29.9°C. Similar results have been achieved using the borehole temperature inversion technique by Dahl-Jensen *et al.* (1998).

The reconstructed Greenland temperature from 1845 to 1993 correlates well with the 10-year running mean Summit temperature (Box *et al.*, 2009), these results confirming the reliability of the Kobashi *et al.* (2011) reconstruction. Current decadal temperatures in Greenland clearly do not exceed the envelope of natural variability over the past 4,000 years.

References

- Box, J.E., Yang, L., and Bromwich, D.H. 2009. Greenland Ice Sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.
- Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221.

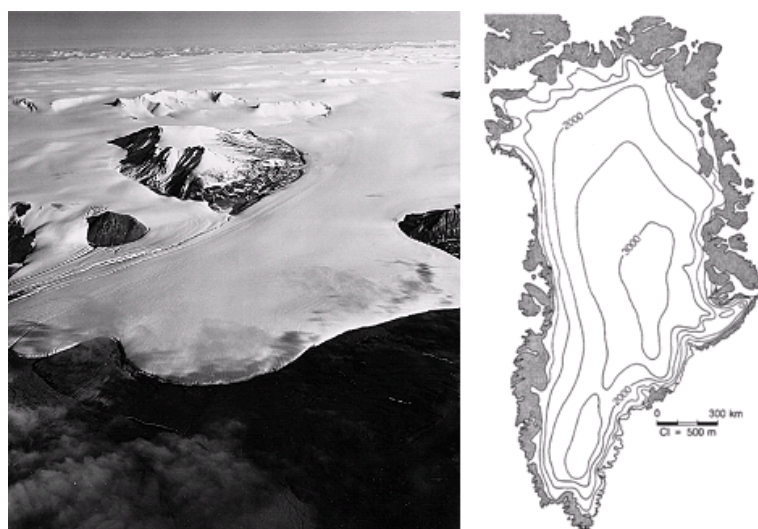


Figure 5.8.4.1. LEFT. Greenland ice sheet (Photo by Austin Post). RIGHT. Contours on the surface of the Greenland ice sheet. Adapted from Easterbrook, D.J. 1993. *Surface processes and landforms*. Prentice Hall.

Climate Change Reconsidered II

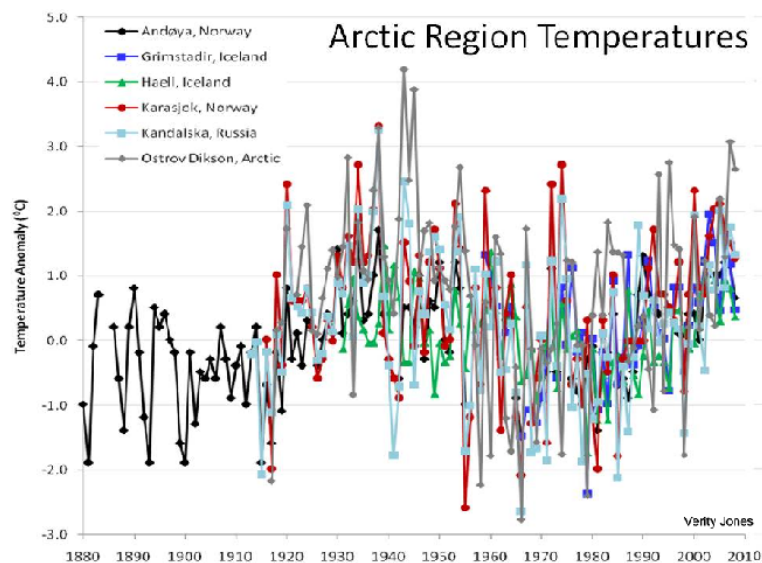


Figure 5.8.4.2. Arctic temperatures from 1880 to 2010. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221; Chylek, P., Dubey, M.K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophysical Research Letters* **33**: 10.1029/2006GL026510.

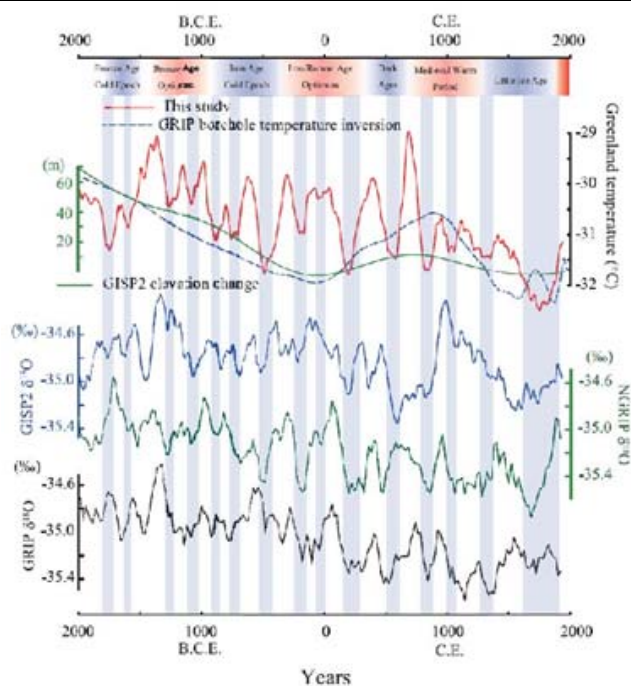


Figure 5.8.4.3. Reconstructed Greenland temperatures compared with oxygen isotope ratios (GISP2, GRIP, and NGRIP) for the past 2,000 years. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

Chylek, P., Dubey, M.K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophysical Research Letters* **33**: 10.1029/2006GL026510.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., and Balling, N. 1998. Past temperatures directly from the Greenland Ice Sheet. *Science* **282**: 268–271.

Easterbrook, D.J. 1993. *Surface processes and landforms*. Prentice Hall.

Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

Other research

Other recent research relevant to the mass balance of the Greenland Ice Cap includes the following papers:

- From long temperature records from southern Greenland, Godthab Nuuk on the west coast and Ammassalik on the east coast, Chylek *et al.* (2006) found “although the whole decade of 1995–2005 was relatively warm, the temperatures at Godthab Nuuk and Ammassalik were not exceptionally high,” and “almost all decades between 1915 and 1965 were warmer than, or at least as warm as, the 1995 to 2005 decade, indicating that the current warm Greenland climate is not unprecedented and that similar temperatures were the norm in the first half of the 20th century.” They note “two periods of intense warming (1995–2005 and 1920–1930) are clearly visible in the Godthab Nuuk and Ammassalik temperature records,” but “the average rate of warming was considerably higher within the 1920–1930 decade than within the 1995–2005 decade.”

Chylek *et al.* (2006) note, “An important question is to what extent can the current (1995–2005) temperature increase in Greenland coastal regions be interpreted as evidence of man-induced global warming?” They conclude, “The Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary

Observations: The Cryosphere

condition for a period of warming to arise,” and “the observed 1995–2005 temperature increase seems to be within the natural variability of Greenland climate.”

- Ettema *et al.* (2009) state “to better quantify and predict the mass balance and freshwater discharge of the Greenland Ice Sheet requires improved knowledge of its surface mass balance (SMB),” defined as the annual sum of mass accumulation (snowfall, rain) and ablation (sublimation, runoff). They apply a regional atmospheric climate model over the Greenland Ice Sheet and its surrounding oceans and islands at the unprecedented high horizontal resolution of ~11 km, coupled to a physical snow model that treats surface albedo as a function of snow/firn/ice properties, meltwater percolation, retention, and refreezing. The atmospheric part of the model was forced at the lateral boundaries and the sea surface by the global model of the European Centre for Medium-Range Weather Forecasts for the period September 1957 to September 2008.

The model projected an annual precipitation for the Greenland ice sheet for 1958–2007 that was up to 24 percent higher, and a surface mass balance that was up to 63 percent higher, than previously thought. The GIS’s SMB averaged 469 ± 41 Gt/year over the study period. Before 1990, none of the mass balance components exhibited a significant trend, but after 1990 a slight downward trend of 12 ± 4 Gt/year occurred in SMB. Though lacking the context of a full mass balance for Greenland, Ettema *et al.* still felt able to conclude, “considerably more mass accumulates on the Greenland Ice Sheet than previously thought,” adjusting earlier estimates upwards by as much as 63 percent.

- Sundal *et al.* (2011) report on five years of satellite observations (1993, 1995–1998) of ice motion in southwest Greenland. As in previous studies, they found although peak ice flow speeds are positively correlated with the degree of melting, mean summer flow rates are not. This is because glacier slow-down usually occurs only when a critical run-off threshold of about 1.4 cm/day is exceeded. In the first half of summer, flow is similar in all years, but increased flow during later summer is 62 ± 16 percent less in warmer years. Accordingly, in warmer years “the period of fast ice flow is three times shorter and, overall, summer ice flow is slower.” Sundal *et al.* concluded, perhaps counterintuitively but as van de Wal *et al.* (2008) showed earlier, “a long-term (17-year) decrease in Greenland’s flow [occurred] during a period of increased melting.”

- Bjork *et al.* (2012) used data gathered by the seventh Thule Expedition (Gabel-Jorgensen, 1935, 1940), which surveyed the southeast coast of Greenland in 1932–1933, comparing the data with later aerial photographs and satellite images in order to study glacial behavior between 1932 and 2010. The terminus regions of 132 glaciers along more than 600 km of the southeast Greenland coastline were included in the study.

Two significant glacier recessional events were identified, one during the 1930s (1933–1943) and another during the 2000s (2000–2010), accompanied by increasing temperatures. Marine-terminating glaciers retreated more rapidly during the recent warming, which was otherwise manifest in similar ways to the 1930s warming—in fact, “many land-terminating glaciers underwent a more rapid retreat in the 1930s than in the 2000s.” Bjork *et al.* point out the recent high rate of retreat may slow when retreating marine-terminating glaciers reach their grounding line and become less sensitive to the influence of ocean temperature (Howat *et al.*, 2008; Moon and Joughin, 2008), and positive or negative feedback mechanisms relating to the cold East Greenland Coastal Current may also come into play (Murray *et al.*, 2010).

- Bergmann *et al.* (2012) reevaluated GIS mass balance over the longer timespan of 2002–2010, using what they view as improved post-processing techniques. They found a decreasing mass loss of the GIS over the last few years for all the considered sources (UTCSR, GFZ, and JPL) and several filtering methods (Gaussian and Gaussian + ICA for averaging radii of 300, 400, and 500 km). Bergmann *et al.* report “the increase in snowfall since winter 2008–2009 in the south and since 2009–2010 in the north, and also a deceleration of the glacier discharge since 2008 reported in several studies using independent data, are responsible for the decrease in mass loss of Greenland.”

- Kjaer *et al.* (2012) used a digital elevation model derived from aerial photographs to extend the record of Dynamic Ice Loss for northwestern Greenland back to 1985. They describe two independent dynamic ice loss events, one extending from 1985 to 1993 and the other from 2005 to 2010, separated by periods of relative ice stability (“limited mass changes”). The ice mass changes were caused primarily by short-lived dynamic ice loss events rather than by changes in the surface mass balance, which, as Kjaer *et al.* point out, “challenges predictions about the future response of the Greenland Ice Sheet to increasing global temperatures.”

Conclusions

As for Antarctica, though perhaps to a lesser degree, the mass balance of the Greenland Ice Sheet (GIS) is of high interest in the context of global warming because the IPCC projects melting of the whole ice sheet would contribute nearly 7 meters to sea-level rise (Bergmann *et al.*, 2012).

Predicting the sea-level response that will occur as a result of changes in the global cryosphere requires an accurate knowledge of the present-day and recent-past mass balance for the major icecaps and glaciers throughout the world as well as a prediction of the stability through time of present-day mass balances. Prior to the availability of satellite measurements, the mass balances of the major ice sheets were poorly known.

Even today, representing these matters accurately remains a difficult task because of the variety and complexity of the processes that control the accumulation and destruction of glacial ice, and because of inadequacies in our measuring systems (Section 5.8.2 above).

The literature summarized above makes clear no empirical evidence yet exists for unusual or unnatural temperature or ice volume changes on the Greenland ice sheet.

References

- Bergmann, I., Ramillien, G., and Frappart, F. 2012. Climate-driven interannual ice mass evolution in Greenland. *Global and Planetary Change* **82-83**: 1–11. doi:10.1016/j.gloplacha.2011.11.005.
- Bjork, A.A., Kjaer, K.H., Korsgaard, N.J., Khan, S.A., Kjeldsen, K.K., Andresen, C.S., Box, J.E., Larsen, N.K., and Funder, S. 2012. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nature Geoscience* 10.1038/NGEO1481.
- Chylek, P., Dubey, M.K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophysical Research Letters* **33**: 10.1029/2006GL026510.
- Ettema, J., van den Broeke, M.R., van Meijgaard, E., van de Berg, W.J., Bamber, J.L., Box, J.E., and Bales, R.C. 2009. Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. *Geophysical Research Letters* **36**: 10.1029/2009GL038110.
- Gabel-Jorgensen, C.A.A. 1935. Dr. Knud Rasmussen's contribution to the exploration of the south-east coast of Greenland, 1931–1933. *Geography Journal* **86**: 32–49.
- Gabel-Jorgensen, C.A.A. 1940. Report on the Expedition—6. Og7. Thule-Expedition til Sydostgronland 1931–1933. *Meddelelser om Gronland* **106**.
- Howat, I.M., Joughin, I., Fahnestock, M., Smith, B.E., and Scambos, T.A. 2008. Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000–06: Ice dynamics and coupling to climate. *Journal of Glaciology* **54**: 646–660.
- Kjaer, K.H., Khan, S.A., Korsgaard, N.J., Wahr, J., Bamber, J.L., Hurkmans, R., van den Broeke, M., Timm, L.H., Kjeldsen, K.K., Bjork, A.A., Larsen, N.K., Jorgensen, L.T., Faerch-Jensen, A., and Willerslev, E. 2012. Aerial photographs reveal late-20th-century dynamic ice loss in northwestern Greenland. *Science* **337**: 569–573.
- Moon, T. and Joughin, I. 2008. Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *Journal of Geophysical Research* **113**: 10.1029/2007JF000927.
- Murray, T., Scharrer, K., James, T.D., Dye, S.R., Hanna, E., Booth, A.D., Selmes, N., Luckman, A., Hughes, A.L.C., Cook, S., and Huybrechts, P. 2010. Ocean regulation hypothesis for glacier dynamics in southeast Greenland and implications for ice sheet mass changes. *Journal of Geophysical Research* **115**: 10.1029/2009JF001522.
- Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P. 2011. Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature* **469**: 521–524.

Earlier research

Other evidence regarding the stability and natural variation of the Greenland ice sheet is described and discussed in the following earlier research papers.

- Krabill *et al.* (2000) used aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999, together with previously reported data from southern Greenland, to evaluate the mass balance of the Greenland Ice Sheet. Above an elevation of 2,000 meters they found areas of both thinning and thickening, and these phenomena nearly balanced each other, so that in the south there was a net thinning of 11 ± 7 mm/year, while in the north there was a net thickening of 14 ± 7 mm/year. The region exhibited a net thickening of 5 ± 5 mm/year; but after correcting for bedrock uplift, which averaged 4 mm/year in the south and 5 mm/year in the north, the average thickening rate decreased to practically nothing. Krabill *et al.* described the net balance as “zero.”

At lower elevations, thinning predominated along approximately 70 percent of the coast. Here, however, data were so sparse (widely spaced flight lines) that the researchers acknowledged, “in order to extend our estimates to the edge of the ice sheet in areas not

Observations: The Cryosphere

bounded by our surveys, we calculated a hypothetical thinning rate on the basis of the coastal positive degree day anomalies.” They then interpolated between this calculated coastal thinning rate and the nearest observed elevation changes to obtain their final estimate of mass balance, a net reduction in ice volume of 51 km³/year. Acknowledging the uncertainty of this result, Krabill *et al.* note changes in ice dynamics, rather than changes in temperature, were the most likely cause of the hypothetical ice sheet thinning.

- Taurisano *et al.* (2004) describe the temperature trends of the Nuuk Fjord, West Greenland, during the past century, in order to assess the local glacial dynamics. Their data show a warming trend for the first 50 years of the 1900s, followed by cooling over the second part of the twentieth century, when the average annual temperatures decreased by approximately 1.5°C. The cooling was accompanied by “a remarkable increase in the number of snowfall days (+59 days)” and affected the summer mean as well as winter temperatures but was not accompanied by any significant change in annual precipitation. Comparison with regional data led Taurisano *et al.* to conclude the Nuuk Fjord climatic history is similar to that recorded at many other stations throughout south and west Greenland (cf. Humlum, 1999; Hanna and Cappelen, 2002, 2003).
- Zwally *et al.* (2005) used satellite radar altimetry to determine the Greenland Ice Sheet is “growing inland with a small overall mass gain,” while thinning at the margins. Similarly, Johannessen *et al.* (2005) found for the 11-year period 1992–2003 the elevation-change rate below 1,500 meters was [negative] 2.0 ± 0.9 cm/year, but “an increase of 6.4 ± 0.2 cm/year is found in the vast interior areas above 1500 meters.” Spatially averaged over the whole ice sheet, this results in a net increase of 5.4 ± 0.2 cm/year (~60 cm over 11 years, or ~54 cm when corrected for isostatic uplift). Zwally *et al.* conclude the GIS experienced no net loss of mass for the decade after 1992, but instead theoretically contributed a 0.03 ± 0.01 mm/year decline in sea level.
- Rignot and Kanagaratnam (2005) used satellite radar interferometry observations of Greenland to detect what they called “widespread glacier acceleration.” Calculating this phenomenon had led to a doubling of the ice sheet mass deficit in the past decade and, therefore, a comparable increase in Greenland’s contribution to rising sea levels, they claim “as more glaciers accelerate ... the contribution

of Greenland to sea-level rise will continue to increase.”

The problem with this conclusion is that instead of using measurements for their evaluation, Rignot and Kanagaratnam used modeled estimates by Hanna *et al.* (2005), who used meteorological models “to retrieve annual accumulation, runoff, and surface mass balance.” When actual measurements of the ice sheet via satellite radar altimetry are employed, a different result is reached—one of near mass balance, as indicated by the work of Zwally *et al.* (2005), Johannessen *et al.* (2005), and others.

- Nick *et al.* (2009) made a comprehensive study of the outlet glaciers that occur around the margins of the Greenland Ice Sheet. They report a recent marked retreat, thinning, and acceleration of most of Greenland’s outlet glaciers south of 70°N, which, given it paralleled a temperature rise, raises concern over future sea-level rise.

To better understand this ice history, the authors developed a numerical ice-flow model to reproduce the changes in one of the largest outlet glaciers, the Helheim Glacier. The model simulations suggest ice acceleration, thinning, and retreat begin at the calving glacier terminus, and then propagate upstream through dynamic coupling along the glacier.

- Sharp and Wang (2009) used scatterometer data to map the timing of the 2000–2004 annual melt and freeze-up on three Eurasian icecaps east of Greenland: Svalbard [Norway], Novaya Zemlya [Russia], and Severnaya Zemlya [Russia]. Their five-year study was placed in context by developing regression relationships between melt season duration and annual (June + August) mean 850-hPa air temperature over each region (from NCEP-NCAR Reanalysis) that could be used to predict the annual melt duration for each year in the 1948–2005 period. The 2000–2004 pentad has the second-longest mean predicted melt duration on Novaya Zemlya (after 1950–1954), and the third longest on Svalbard (after 1950–1954 and 1970–1974) and Severnaya Zemlya (after 1950–1954 and 1955–1959), with respect to all discrete five-year periods between 1950 and 2004.
- Wake *et al.* (2009) also attempted to assess the rapidity of Greenland ice melt, using a surface mass balance model. The authors reconstructed the 1866–2005 surface mass-balance (SMB) history of the Greenland ice sheet on a 5 x 5 km grid, using a runoff-retention model based on the positive degree, which they forced with data sets of temperature and precipitation dating back to 1866. They sought to compare “the response of the ice sheet to a recent

period of warming and a similar warm period during the 1920s to examine how exceptional the recent changes are within a longer time context.”

The model outputs suggested present-day SMB changes “are not exceptional within the last 140 years,” with the SMB decline over 1995–2005 being no different from that of 1923–1933. Wake *et al.* conclude the recent and extensively monitored SMB changes (Krabill *et al.*, 2004; Luthcke *et al.*, 2006; Thomas *et al.*, 2006) “represent natural sub-decadal fluctuations in the mass balance of the ice sheet and are not necessarily the result of anthropogenic-related warming.”

- In keeping with these earlier findings, Murray *et al.* (2010) report the Greenland Ice Sheet’s annual ice discharge doubled during the 2000s, accompanied by outlet glacier thinning, accelerating, and retreating. This phase of fast discharge was followed by slowdown, for in 2006 two of the largest glaciers in the sector, Helheim and Kangerdlugssuaq, slowed down simultaneously (Howat *et al.*, 2007), ceased thinning (Stearns and Hamilton, 2007; Howat *et al.*, 2007), and even readvanced (Joughin *et al.*, 2008). Other nearby glaciers behaved in similar fashion (Howat *et al.*, 2008; Moon and Joughin, 2008), making the slowdown from 2006 widespread, synchronized throughout southeast Greenland, and lasting until at least 2008.

Conclusions

Arguments similar to those offered in discussing the impact of global warming on Antarctic ice mass-balance (Section 5.8.3 above) apply also to Greenland. However, much longer instrumental temperature records exist for Greenland than Antarctica, and these show beyond doubt that previous natural warming cycles at least equalled, and more probably exceeded, the mild warming at the end of the twentieth century.

In addition, several Greenland studies have stressed ice mass balance change often results from internal dynamics, and no simple relationship exists between glacial melt and increasing temperature. For example, in studying the Helheim and nearby glaciers, Nick *et al.* (2009) concluded their modeling showed “tidewater outlet glaciers should adjust extremely rapidly to changing boundary conditions at the calving terminus, which indicates that the recent rates of mass loss in Greenland’s outlet glaciers are a transient phenomenon, and should not be extrapolated into the future.”

Despite concerns expressed about global warming becoming increasingly intense in its effects in the

Arctic over the past two decades, conditions during the middle of the twentieth century seem to have been in this respect even more extreme than at any subsequent time, especially on the icecaps and associated glaciers studied by Sharp and Wang (2009), who concluded “the 1950–54 pentad ... experienced the longest melt season of the past 55 years on all three of the large Eurasian Arctic ice caps.”

Meanwhile, many of Greenland’s outlet glaciers debouch directly into the ocean, which makes the work of Murray *et al.* (2010) particularly pertinent. They conclude an oscillatory mechanism is at work, whereby increasing ice wastage flow causes glacial termini to push out into warmer ocean water, there melting to enhance the rate of cold water input into the East Greenland Coastal Current, thus in turn weakening its melting capacity. Murray *et al.* conclude their research suggests the presence of “a negative feedback that currently mitigates against continued very fast loss of ice from the ice sheet in a warming climate,” noting “we should expect similar speedup and slowdown events of these glaciers in the future, which will make it difficult to elucidate any underlying trend in mass loss resulting from changes in this sector of the ice sheet.”

Ettema *et al.* (2009) recently concluded “considerably more mass accumulates on the Greenland Ice Sheet than previously thought,” adjusting upwards earlier estimates by as much as 63 percent, which suggests the Northern Hemisphere’s largest ice sheet is not in imminent danger of disintegration.

References

- Ettema, J., van den Broeke, M.R., van Meijgaard, E., van de Berg, W.J., Bamber, J.L., Box, J.E., and Bales, R.C. 2009. Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. *Geophysical Research Letters* **36**: 10.1029/2009GL038110.
- Hanna, E. and Cappelen, J. 2002. Recent climate of Southern Greenland. *Weather* **57**: 320–328.
- Hanna, E. and Cappelen, J. 2003. Recent cooling in coastal southern Greenland and relation with the North Atlantic Oscillation. *Geophysical Research Letters* **30**: 1132.
- Hanna, E., Huybrechts, P., Janssens, I., Cappelin, J., Steffen, K., and Stephens, A. 2005. Runoff and mass balance of the Greenland Ice Sheet: 1958–2003. *Journal of Geophysical Research* **110**: 10.1029/2004JD005641.
- Howat, I.M., Joughin, I., and Scambos, T.A. 2007. Rapid

Observations: The Cryosphere

changes in ice discharge from Greenland outlet glaciers. *Science* **315**: 1559–1561.

Howat, I.M., Joughin, I., Fahnestock, M., Smith, B.E., and Scambos, T.A. 2008. Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000–2006: ice dynamics and coupling to climate. *Journal of Glaciology* **54**: 646–660.

Humlum, O. 1999. Late-Holocene climate in central West Greenland: meteorological data and rock-glacier isotope evidence. *The Holocene* **9**: 581–594.

Hvidberg, C.S. 2000. When Greenland ice melts. *Nature* **404**: 551–552.

Johannessen, O.M., Khvorostovsky, K., Miles, M.W., and Bobylev, L.P. 2005. Recent ice-sheet growth in the interior of Greenland. *Science* **310**: 1013–1016.

Joughin, I., Howat, I., Alley, R.B., Ekstrom, G., Fahnestock, M., Moon, T., Nettles, M., Truffer, M., and Tsai, V.C. 2008. Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq glaciers, Greenland. *Journal of Geophysical Research* **113**: 10.1029/2007JF000837.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J. 2000. Greenland ice sheet: High-elevation balance and peripheral thinning. *Science* **289**: 428–430.

Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., and Yungel, J. 2004. Greenland Ice Sheet: increased coastal thinning. *Geophysical Research Letters* **31**: 10.1029/2004GL021533.

Luthcke, S.B., Zwally, H.J., Abdalati, W., Rowlands, D.D., Ray, R.D., Nerem, R.S., Lemoine, F.G., McCarthy, J.J., and Chinn, D.S. 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. *Science* **314**: 1286–1289.

Moon, T. and Joughin, I. 2008. Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *Journal of Geophysical Research* **113**: 10.1029/2007JF000927.

Murray, T., Scharrer, K., James, T.D., Dye, S.R., Hanna, E., Booth, A.D., Selmes, N., Luckman, A., Hughes, A.L.C., Cook, S., and Huybrechts, P. 2010. Ocean regulation hypothesis for glacier dynamics in southeast Greenland and implications for ice sheet mass changes. *Journal of Geophysical Research* **115**: 10.1029/2009JF001522.

Nick, F.M., Vieli, A., Howat, I.M., and Joughin, I. 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience* **2**: 10.1038/NGEO394.

Rignot, E. and Kanagaratnam, P. 2005. Changes in the

velocity structure of the Greenland Ice Sheet. *Science* **311**: 986–990.

Sharp, M. and Wang, L. 2009. A five-year record of summer melt on Eurasian Arctic ice caps. *Journal of Climate* **22**: 133–145.

Taurisano, A., Boggild, C.E., and Karlsen, H.G. 2004. A century of climate variability and climate gradients from coast to ice sheet in West Greenland. *Geografiska Annaler* **86A**: 217–224.

Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C. 2006. Progressive increase in ice loss from Greenland. *Geophysical Research Letters* **33**: 10.1029/GL026075.

Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I., and Milne, G.A. 2009. Surface mass-balance changes of the Greenland ice sheet since 1866. *Annals of Glaciology* **50**: 176–184.

Zwally, H.J., Giovinetto, M.B., Li, J., Cornejo, H.G., Beckley, M.A., Brenner, A.C., Saba, J.L., and Yi, D. 2005. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *Journal of Glaciology* **51**: 509–527.

5.9 Mountain Glaciers

Over periods of decades to millennia, most valley glaciers' ice either extends in length down-valley (meaning accumulation must be exceeding melting), or shrink in size or retreat up-valley (meaning melting must be exceeding accretion).

5.9.1 Holocene glacial history

Few quantitative observations of glacier extent exist prior to about 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Glacier retreat has not been constant over the past several centuries. Instead, glaciers advanced and retreated multiple times as global climate cooled and warmed repeatedly as Earth passed through and then gradually thawed out from the Little Ice Age.

Was the most recent retreat driven by human-caused global warming? For the most part certainly not, because most of the retreat since the Little Ice Age occurred long before human-related carbon dioxide emissions reached a level where they conceivably could have been a factor. Achieving a proper perspective on the advance and retreat of

alpine glaciers therefore requires data be viewed in the context of Holocene (last 10,000 years) glacial advance and retreat.

Barclay *et al.* (2009) have provided an extensive and up-to-date review of what is known about Alaskan Holocene glacial activity and its relationship to temperature. They found the “termini of land-based valley glaciers were in retracted positions during the early to middle Holocene,” but “neoglaciation was underway in some areas by 4.5–4.0 ka and major advances of land-based termini occurred by 3.0 ka.” Most dramatic, however, were the Little Ice Age (LIA) glacial advances, which culminated in two phases in the 1540s–1710s and 1810s–1880s, of which they state, “moraines of these middle and late LIA maxima are invariably the Holocene maxima in coastal southern Alaska,” adding, “LIA advances are also recognized as major expansions in all glacierized mountain ranges in Alaska.” In addition, they state researchers have determined “Holocene fluctuations of Alaskan land-terminating glaciers have primarily been forced by multi-decadal and longer timescale changes in temperature.”

These observations suggest changes in glaciation in Alaska during the twentieth century likely started after the coldest portion of the Holocene, the Little Ice Age, when Earth cooled and then warmed again quite naturally, without any reference to rising human atmospheric CO₂ contributions.

Reference

Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Holocene glacier fluctuations in Alaska. *Quaternary Science Reviews* 28: 2034–2048.

Other research

Similar inferences to those from drawn from Alaska have been drawn from other summaries of Holocene glacial history worldwide, including the following.

- Rodbell *et al.* (2009) reported on Andean glaciers in South America. These authors updated “the chronology of Andean glaciation during the Lateglacial and the Holocene from the numerous articles and reviews published over the past three decades,” noting the Andes “offer an unparalleled opportunity to elucidate spatial and temporal patterns of glaciation along a continuous 68-degree meridional transect.” They found “all presently glacierized mountain ranges contain multiple moraines deposited during the last 450 years” and “these correlate with the Little Ice Age as defined in the Northern

Hemisphere.” In addition, they note most Andean regions “reveal a nearly continuous temporal distribution of moraines during the Little Ice Age.”

The occurrence of the Little Ice Age in essentially all of the glaciated portions of the Northern Hemisphere and the great meridional expanse of most of Andean South America, as well as the similar glacial activity of both parts of the planet during this time period, provide strong support for the proposition that montane glaciation began to retreat when much of the world commenced its return to its current, milder climatic state from what could be called the Holocene’s “thermal basement,” i.e., the Little Ice Age.

- In another study of Holocene glacier change, Nesje (2009) compiled, assessed, and evaluated “evidence of Late Glacial and Holocene glacier fluctuations in Scandinavia as deduced from ice-marginal features, marginal moraines, proglacial terrestrial and lacustrine sites, using especially new information that has become available since the review paper published by Karlen (1988).” Nesje reports data indicate significant late-glacial ice-sheet fluctuations and glacial contraction during the early and mid-Holocene and subsequent Neoglacial expansion, peaking during the Little Ice Age. These observations, he writes, are “in good agreement with other presently glaciated regions in the world,” as described by Solomina *et al.* (2008) and references therein.

- Other authors have confirmed the Little Ice Age in Scandinavia, as in most parts of the world where glaciers formed and grew during that period, was a depressing and dangerous time (Luckman, 1994; Villalba, 1994; Smith *et al.*, 1995; Naftz *et al.*, 1996). Alpine glaciers advanced in virtually all mountainous regions of the globe during that period, eroding large areas of land and producing masses of debris. Ice streamed down mountain slopes to carve paths through the landscape, moving rocks and destroying all vegetation in their paths (Smith and Laroque, 1995).

Continental glaciers and sea ice expanded their ranges as well during this period (Grove, 1988; Crowley and North, 1991). Near Iceland and Greenland, in fact, the expansion of sea ice during the Little Ice Age was so great it isolated the Viking colony established in Greenland during the Medieval Warm Period, leading to its eventual abandonment (Bergthorsson, 1969; Dansgaard *et al.*, 1975; Pringle, 1997).

- Another Holocene study, this time of European

Observations: The Cryosphere

glacial activity by Ivy-Ochs *et al.* (2009), presented “a summary of the evidence for suggested periods of glacier advance during the final phase of the Alpine Lateglacial and the Holocene,” interweaving “data obtained from ^{10}Be surface exposure dating, radiocarbon dating of wood and peat washed out from the presently melting glacier tongues, dendrochronological investigations on wood from the glacierized basins, tree-line studies and archaeological evidence.”

The authors found “the earliest Holocene (between 11.6 and about 10.5 ka) was still strongly affected by the cold climatic conditions of the Younger Dryas and the Preboreal oscillation,” but “at or slightly before 10.5 ka rapid shrinkage of glaciers to a size smaller than their late 20th century size reflects markedly warmer and possibly also drier climate.” After 3.3 ka, however, “climate conditions became generally colder and warm periods were brief and less frequent.” Finally, they note “glaciers in the Alps attained their Little Ice Age maximum extents in the 14th, 17th and 19th centuries, with most reaching their greatest Little Ice Age extent in the final 1850/1860 AD advance.”

Like their alpine glacier counterparts in Scandinavia, as described by Nesje (2009), glaciers of the European Alps also reached their maximum Holocene extensions close to the end of the Little Ice Age. At that time there existed the greatest potential for significant glacial retreat of the entire Holocene interglacial, for in an oscillatory climatic regime, the point of lowest temperature decline also represents the point of the greatest potential for a significant temperature increase. It would be expected, then, that the subsequent temperature recovery of Earth would be quite substantial, as there was much prior cooling to be overcome to return the planet to a climatic state more characteristic of the bulk of the Holocene.

- Considering glacial change over a shorter timeframe, Vincent *et al.* (2007) analyzed the impact of climate change over the past 100 years on high-elevation glaciated areas of the Mont Blanc range, including the ice fields that cover the Mont Blanc (4,808 m) and Dôme du Goûter (4,300 m) peaks. Surface ablation is negligible for these high-elevation areas, and the surface mass balance is mainly controlled by snow accumulation.

At Dôme du Goûter, ice fluxes were calculated through two transversal sections by two independent methods in order to assess long-term surface accumulation. A comparison between these results and recent accumulation observations, together with the strong relationship between valley precipitation

and snow accumulation, suggests surface accumulation rates did not change significantly over the entire twentieth century. Vincent *et al.* state “the most striking features ... are the small thickness changes observed over the 20th century. For both areas, thickness variations do not exceed ± 15 m. The average changes are +2.6 m at Dôme du Goûter and -0.3 m at Mont Blanc. Considering the uncertainty interval, i.e., ± 5 m, it can be concluded that no significant thickness change is detectable over most of these areas.” These findings show these high-elevation glaciated areas have not been significantly affected by climate change over the past 100 years.

- Kaser *et al.* (2010) examined the ice fields that top Mt. Kilimanjaro’s highest peak, Kibo. Kaser *et al.* write these features have garnered “particular attention” since Irion (2001) attributed modern changes in them to “increased air temperature in the context of global warming” and Thompson *et al.* (2002) reported what they described as the “near extinction of the ice on Kibo,” which they characterized as being “unprecedented over the last 11,700 years.” Kaser *et al.* (2004) developed an alternative hypothesis, namely that atmospheric moisture controls the modern-time glacier changes on Kibo, as Kaser *et al.* (2010) indicate is also suggested by the work of Molg and Hardy (2004), Cullen *et al.* (2006, 2007), and Molg *et al.* (2003, 2006, 2009a, b). This finding, in their words, “rules out rising local air temperature (i.e. on the peak of Kibo) as the main driver of observed changes during the last 120 years.”

Based on their review of all available information on present-day phenomena that control the glaciers on Kilimanjaro, Kaser *et al.* (2010) conclude “minor changes in thickness have no impact on the changing surface area of the tabular plateau glaciers,” while noting “plateau glacier area decrease has been strikingly constant over the twentieth century” and “ablation rates of the ice walls are [also] persistently constant.” In addition, their analyses suggest the mountain’s plateau ice “may have come and gone repeatedly throughout the Holocene” and the reduction of plateau ice in modern times “is controlled by the absence of sustained regional wet periods rather than changes in local air temperature on the peak of Kilimanjaro.”

Conclusions

Studies of Holocene glacial history show valley glaciers have waxed and waned worldwide for the past ten millennia. These glacial advances and retreats have occurred in sympathy with natural climate forcings. No evidence exists that unnatural glacial

retreat occurred in the late twentieth century forced by human carbon dioxide emissions.

References

- Bergthorsson, P. 1969. An estimate of drift ice and temperature in 1000 years. *Jökull* **19**: 94–101.
- Crowley T.J. and North, G.R. 1991. *Palaeoclimatology*. Oxford University Press, Oxford.
- Cullen, N.J., Molg, T., Hardy, D.R., Steffen, K., and Kaser, G. 2007. Energy-balance model validation on the top of Kilimanjaro, Tanzania, using eddy covariance data. *Annals of Glaciology* **46**: 227–233.
- Cullen, N.J., Molg, T., Kaser, G., Hussein, K., Steffen, K., and Hardy, D.R. 2006. Kilimanjaro: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters* **33**: 10.1029/2006GL0227084.
- Dansgaard, W., Johnsen, S.J., Reeh, N., Gundestrup, N., Clausen, H.B., and Hammer, C.U. 1975. Climate changes, Norsemen, and modern man. *Nature* **255**: 24–28.
- Grove, J.M. 1988. *The Little Ice Age*. Routledge, London.
- Irion, R. 2001. The melting snows of Kilimanjaro. *Science* **291**: 1690–1691.
- Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149.
- Karlen, W. 1988. Scandinavian glacial and climatic fluctuations during the Holocene. *Quaternary Science Reviews* **7**: 199–209.
- Kaser, G., Molg, T., Cullen, N.J., Hardy, D.R., and Winkler, M. 2010. Is the decline of ice on Kilimanjaro unprecedented in the Holocene? *The Holocene* **20**: 1079–1091.
- Kaser, G., Hardy, D.R., Molg, T., Bradley, R.S., and Hyera, T.M. 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *International Journal of Climatology* **24**: 329–339.
- Luckman, B.H. 1994. Evidence for climatic conditions between ca. 900–1300 A.D. in the southern Canadian Rockies. *Climatic Change* **26**: 171–182.
- Molg, T., Chiang, J.C.H., Gohm, A., and Cullen, N.J. 2009a. Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modeling. *Quarterly Journal of the Royal Meteorological Society* **135**: 1439–1455.
- Molg, T., Cullen, N.J., Hardy, D.R., Winkler, M., and Kaser, G. 2009b. Quantifying climate change in the tropical mid-troposphere over East Africa from glacier shrinkage on Kilimanjaro. *Journal of Climate* **22**: 4162–4181.
- Molg, T. and Hardy, D.R. 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research* **109**: 1–13.
- Molg, T., Hardy, D.R., and Kaser, G. 2003. Solar-radiation-maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *Journal of Geophysical Research* **108**: 10.1029/2003JD003546.
- Molg, T., Renold, M., Vuille, M., Cullen, N.J., Stocker, T.F., and Kaser, G. 2006. Indian Ocean zonal mode activity in a multi-century integration of a coupled AOGCM consistent with climate proxy data. *Geophysical Research Letters* **33**: 10.1029/2006GL026384.
- Naftz, D.L., Klusman, R.W., Michel, R.L., Schuster, P.F., Reddy, M.M., Taylor, H.E., Yanosky, E.A., and McConnaughey, E.A. 1996. Little Ice Age evidence from a south-central North American ice core, U.S.A. *Arctic and Alpine Research* **28**: 35–41.
- Nesje, A. 2009. Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. *Quaternary Science Reviews* **28**: 2119–2136.
- Pringle, H. 1997. Death in Norse Greenland. *Science* **275**: 924–926.
- Rodbell, D.T., Smith, J.A., and Mark, B.G. 2009. Glaciation in the Andes during the Lateglacial and Holocene. *Quaternary Science Reviews* **28**: 2165–2212.
- Smith, D.J. and Laroque, C.P. 1995. Dendroglaciological dating of a Little Ice Age glacier advance at Moving Glacier, Vancouver Island, British Columbia. *Géographie physique et Quaternaire* **50**: 47–55.
- Smith, D.J., McCarthy, D.P., and Colenutt, M.E. 1995. Little Ice Age glacial activity in Peter Lougheed and Elk Lakes provincial parks, Canadian Rocky Mountains. *Canadian Journal of Earth Science* **32**: 579–589.
- Solomina, O., Haeberli, W., Kull, C., and Wiles, G. 2008. Historical and Holocene glacier-climate variations: general concepts and overview. *Global and Planetary Change* **60**: 1–9.
- Thompson, L.G., Mosely-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotto, T.A., Lin, P.-N., Mikhalenko, V.N., Hardy, D.R., and Beer, J. 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* **298**: 589–593.
- Villalba, R. 1994. Tree-ring and glacial evidence for the medieval warm epoch and the Little Ice Age in southern

Observations: The Cryosphere

South America. *Climatic Change* **26**: 183–97. doi:10.1007/BF01092413.

Vincent, C., Le Meur, E., Six, D., Funk, M., Hoelzle, M., and Preunkert, S. 2007. Very high-elevation Mont Blanc glaciated areas not affected by the 20th century climate change. *Journal of Geophysical Research* **112**: D09120, doi:10.1029/2006JD007407.

5.9.2 European Alpine Glaciers

European alpine glaciers provide most of the longer historical and instrumented records of fluctuations in valley glacier size. Despite a large corpus of research literature, no paper yet demonstrates any correlation between increasing atmospheric CO₂ levels and the glacial melting projected by IPCC computer models, or supports their claim that Earth has recently warmed to its highest temperature of the past thousand years.

We summarize below recent studies of European glaciers, some of which have been stable or even advancing over the past 30 years despite the mild late twentieth century warming.

Joerin *et al.* (2006) used radiocarbon dating of materials found in subglacial and proglacial sediment, together with previously published data, to construct a Holocene glacial history of the Swiss Alps over the past ten thousand years. The results demonstrate “alpine glacier recessions occurred at least 12 times during the Holocene” and, glacier retreats have decreased in frequency since 7,000 years ago, and especially since 3,200 years ago, a trend that culminated in the Little Ice Age maximum advance. Moreover, the last major glacial retreat occurred between 1,400 and 1,200 years ago, a little before the Medieval Warm Period. A similar retreat occurred in the Great Aletsch Glacier between 1,200 and 800 years ago (Holzhauser *et al.*, 2005)

Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 to compute the yearly mass balances of the Swiss Silvretta, Rhone, Aletsch, and Gries glaciers. All four glaciers have steadily, if episodically, shrunk since 1865 (Figure 5.9.2.1), with no acceleration of the shrinkage over time, which is required by the anthropogenic global warming hypothesis.

Linderholm *et al.* (2007) examined the world’s longest available mass-balance record from a mountain glacier, the Storglaciaren in northern Sweden. The record is well correlated with the records of other glaciers in the same region (Holmlund and Jansson, 1999), suggesting it is representative of northern Swedish glaciers. Figure

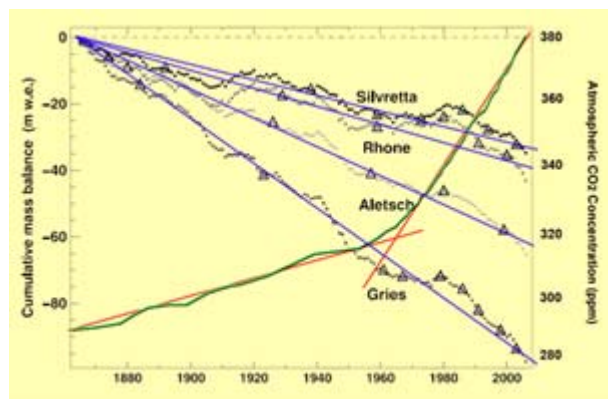


Figure 5.9.2.1. Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in the Swiss Alps to compute the yearly mass balances of four glaciers (linear trends fitted). Green line indicates atmospheric CO₂ concentrations, with two fitter linear segments (red lines). Adapted from Huss, M., Bauder, A., Funk, M., and Hock, R. 2008. Determination of the seasonal mass balance of four Alpine glaciers since 1865. *Journal of Geophysical Research* **113**: 10.1029/2007JF000803.

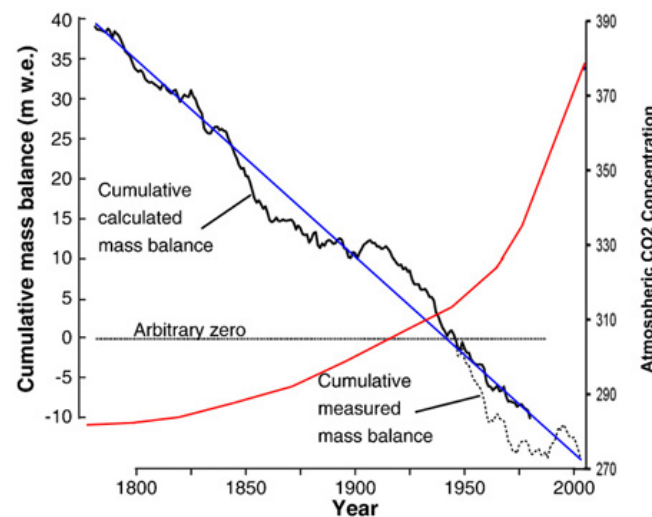


Figure 5.9.2.2. The cumulative reconstructed net mass balance history of Sweden’s Storglaciaren, to which we have added the fit-by-eye descending linear relationship (blue line), and the history of the atmosphere’s CO₂ concentration (red line). Adapted from Linderholm, H.W., Jansson, P., and Chen, D. 2007. A high-resolution reconstruction of Storglaciaren mass balance back to 1780/81 using tree-ring and circulation indices. *Quaternary Research* **67**: 12–20.

5.9.2.2 shows the Storglaciaren mass balance, plotted together with the record of atmospheric CO₂ over the same time period. It is evident the same pattern of progressive ice shrinkage seen in glaciers in the

European Alps occurs at Storglaciaren, and no acceleration of melting occurs during the time of strong CO₂ increase in the second half of the twentieth century.

D'Orefice *et al.* (2000) derived a post-Little Ice Age (LIA) history for the southernmost glacier of Europe, Ghiacciaio del Calderone. The surface area of this glacier underwent slow ice wastage from 1794 to 1884, after which a more rapid reduction in area continued to 1990, by which time the glacier had lost about half its LIA surface area.

Other European glaciers show a different pattern and have not experienced consistent, progressive loss of mass. For example, glaciers in the Central Swiss Alps experienced two periods of advance, around 1920 and 1980 (Hormes *et al.*, 2001). Braithwaite (2002) reported for the period 1980–1995 “Scandinavian glaciers [have been] growing, and glaciers in the Caucasus are close to equilibrium”; and Braithwaite and Zhang (2000) reported a significant upward trend in the mass balance of Sweden’s Storglaciaren over the past 30–40 years. Additional evidence for post-LIA glacial expansion is provided by the Solheimajokull outlet glacier, southern coast of Iceland. Mackintosh *et al.* (2002) report a post-LIA minimum of 13.8 km length for this glacier in 1970, which thereafter expanded to 14.3 km by 1995. The minimum length of 13.8 km observed in 1970 also did not eclipse an earlier 300-year minimum length of 13.2 km which occurred in 1783.

Recent glacial advances also have occurred in Norway. Chinn *et al.* (2005) report glacial recession was most strongly expressed there in the middle of the twentieth century during the 1915 to 1945 warm period, ending during the late 1950s to early 1960s; then, after some years with more or less stationary glacier front positions, the glaciers began to advance during the 1945 to 1977 cool period, accelerating in the late 1980s. Around 2000, some of the glacial advance began to slow, though “most of the larger outlets with longer reaction times are continuing to advance.” Chinn *et al.* report “the distances regained and the duration of this recent advance episode are both far greater than any previous readvance since the Little Ice Age maximum, making the recent resurgence a significant event.” Much the same changes have occurred since 1988 “at all [western] maritime glaciers in both southern and northern Norway.”

Conclusions

The studies summarized above show no European-wide correlation exists between increasing atmospheric CO₂ levels and simple glacial melting. Instead, European glaciers display an episodic history, with phases of both retreat and advance throughout the Holocene and over the past quarter-century. During the period over which the IPCC claims Earth has warmed to its highest temperature of the past thousand years, some glaciers advanced, others retreated, and others remained essentially stable.

The histories of glaciers such as the Storglaciaren, which display cumulative post-Little Ice Age retreats, provide no compelling evidence that the retreat had anything to do with the air’s CO₂ content, not least because retreat commenced long before significant levels of industrial emissions had built up. As much to the point, a glacier like the Great Aletsch Glacier attained a length in AD 1000 only slightly less than its length today—despite there having been fully 100 ppm less CO₂ in the air then than there is today.

It is clear the ice-loss history of European glaciers was not influenced by the increase in the rate-of-rise of the air’s CO₂ content that occurred between 1950 and 1970; their rate of shrinkage also was not materially increased by what the IPCC calls the unprecedented warming of the past few decades.

References

- Braithwaite, R.J. 2002. Glacier mass balance: the first 50 years of international monitoring. *Progress in Physical Geography* 26: 76–95.
- Braithwaite, R.J. and Zhang, Y. 2000. Relationships between interannual variability of glacier mass balance and climate. *Journal of Glaciology* 45: 456–462.
- Chinn, T., Winkler, S., Salinger, M.J., and Haakensen, N. 2005. Recent glacier advances in Norway and New Zealand: A comparison of their glaciological and meteorological causes. *Geografiska Annaler* 87A: 141–157.
- D'Orefice, M., Pecci, M., Smiraglia, C., and Ventura, R. 2000. Retreat of Mediterranean glaciers since the Little Ice Age: Case study of Ghiacciaio del Calderone, central Apennines, Italy. *Arctic, Antarctic, and Alpine Research* 32: 197–201.
- Holmlund, P. and Jansson, P. 1999. The Tarfala mass balance programme. *Geografiska Annaler* 81A: 621–631.
- Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* 15: 789–801.

Observations: The Cryosphere

Hormes, A., Müller, B.U., and Schlüchter, C. 2001. The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *The Holocene* **11**: 255–265.

Huss, M., Bauder, A., Funk, M., and Hock, R. 2008. Determination of the seasonal mass balance of four Alpine glaciers since 1865. *Journal of Geophysical Research* **113**: 10.1029/2007JF000803.

Joerin, U.E., Stocker, T.F., and Schlüchter, C. 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene* **16**: 697–704.

Linderholm, H.W., Jansson, P., and Chen, D. 2007. A high-resolution reconstruction of Storglaciaren mass balance back to 1780/81 using tree-ring and circulation indices. *Quaternary Research* **67**: 12–20.

Mackintosh, A.N., Dugmore, A.J., and Hubbard, A.L. 2002. Holocene climatic changes in Iceland: evidence from modeling glacier length fluctuations at Solheimajokull. *Quaternary International* **91**: 39–52.

5.9.3 Asia: Himalayan Glacier History

Concern about melting Himalayan glaciers has been led by the IPCC. Alarmist assertions have included claims that almost all Indian glaciers, including the Gangotri Glacier, will vanish from Earth in the next few decades, accompanied first by flooding and then by the drying of glacial-fed rivers, desertification, sea-level rise, submergence of coastal areas, spread of diseases, and a drop in the production of food grains—all, of course, as a result of anthropogenic global warming. Early in 2011 it was discovered the IPCC’s key reference for such alarmist claims was an unrefereed report published by an environmentalist lobby group.

Meanwhile, Bali *et al.* (2011) carried out a comprehensive review of Himalayan glaciers, noting the Geological Survey of India has identified more than 9,000 valley glaciers in India and at least 2,000 more in Nepal and Bhutan (Raina, 2006), few of which are instrumented to modern standards. Hewitt (2010), investigating glaciers in the Karakoram, comments, “emerging evidence suggests that alarmist reports about the Himalaya are, at best, exaggerated,” as also pointed out by Raina (2009) and Armstrong (2010). There is strong evidence for anomalous post-Little Ice Age glacier expansion in parts of the Karakoram, nourished not only by snowfall but also by avalanche contributions.

Hewitt (2005, 2011) found Karakoram glaciers have declined by only 5 percent or so since the early twentieth century, mainly between the 1920s and

1960s. Ice loss slowed in the 1970s (Mayewski and Jenschke, 1979) during the 1945–1977 cool period, when some glaciers underwent modest advances (Kotlyakov, 1997), and modest retreat then prevailed again from the mid-1980s through the 1990s warm period. Most recently, “since the late 1990s we have reports of glaciers stabilizing and, in the high Karakoram, advancing (Hewitt, 2005; Immerzeel *et al.*, 2009),” while “total snow cover has been increasing in the high Karakoram (Naz *et al.*, 2009).”

Such a glacial history cannot have been driven simply by increasing anthropogenic carbon dioxide emissions, but rather must reflect the complex interaction of the several major processes that control glacier dynamics. In the high Himalaya, Hewitt points out, the extent and sustained high elevations of the main Karakoram, together with the “all-year accumulation regime, help to buffer glaciers against ‘warming,’” should it start to occur again. He also notes “various investigations report cooler summers recently and greater summer cloudiness and snow cover (Fowler and Archer, 2006; Naz *et al.*, 2009; Scherler *et al.*, 2011), which potentially should lead to reduced average ablation rates or numbers of ‘ablation days.’”

References

Armstrong, R.L. 2010. *The Glaciers of the Himalayan-Hindu-Kush Region*. Technical Paper of The International Centre for Integrated Mountain Development, Kathmandu, Nepal.

Bali, R., Agarwal, K.K., Ali, S.N., and Srivastava, P. 2011. Is the recessionary pattern of Himalayan glaciers suggestive of anthropogenically induced global warming? *Arabian Journal of Geosciences* **4**: 1087–1093.

Fowler, H.J. and Archer, D.R. 2006. Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate* **19**: 4276–4293.

Hewitt, K. 2005. The Karakoram anomaly? Glacier expansion and the ‘elevation effect,’ Karakoram Himalaya. *Mountain Research and Development* **25**: 332–340.

Hewitt, K. 2011. Glacier change, concentration, and elevation effects in the Karakoram Himalaya, upper Indus Basin. *Mountain Research and Development* **31**: 188–200.

Immerzeel, W.W., Droogers, P., de Jong, S.M., and Bierkens, M.F.P. 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment* **113**: 40–49.

Kotlyakov, V.M. (Ed.). 1997. *World Atlas of Snow and Ice Resources*. Institute of Geography, Academy of Sciences, Moscow, Russia.

Mayewski, P.A. and Jeschke, P.A. 1979. Himalayan and trans-Himalayan glacier fluctuations since AD 1812. *Arctic and Alpine Research* **11**: 267–287.

Naz, B.S., Bowling, L.C., Diffenbaugh, N.S., Owens, P., Ashfaq, M., and Shafiqur-Rehman, S. 2009. *Hydrological Sensitivity of the Upper Indus River to Glacier Changes in the Karakoram Himalaya Region*. Poster C31C-0455, November 2009 Meeting, American Geophysical Union, San Francisco, California, USA.

Raina, V.K. 2009. Himalayan Glaciers: A State-of-Art Review of Glacial Studies, Glacial Retreat and Climate Change. Ministry of Environment and Forests, New Delhi, India.

Scherler, D., Brookhagen, B., and Strecker, M.R. 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience* **4**: 156–159.

Other research

Other evidence regarding the stability and natural variation of Himalayan glaciers, especially those in the western Karakoram Ranges, is further described and discussed in the following research papers.

- Schmidt and Nusser (2009) used a multitemporal/multiscale approach to studying glacial change in the Nanga Parbat region, Northern Pakistan, using historical data, repeat photography, and satellite imagery to develop a 70-year history of the behavior of that region's Raikot Glacier. They found only "relatively small rates of recession and surface changes over the last seven decades," noting "some well-defined large boulders remain in the same position in 2006 as in 1934," which indicates a high stability for the proglacial area and lateral moraines. In these respects, the Raikot Glacier is similar to "most debris-covered glaciers in the northwest Himalaya and in the nearby Karakoram, Hindu Kush and Kun Lun ranges, Raikot Glacier [which] show only minor retreating rates since the 1980s." Schmidt and Nusser report "glacier fluctuations over the past 70 years are characterized by retreat between the 1930s and 1950s, a marked advance between the 1950s and 1980s, and a relatively stable situation after 1992," but with no general trend of reducing ice mass since the 1930s.
- Chaujar (2009) used lichenometric dating of loop moraines on the Chorabari Glacier, Garhwal Himalayas to establish its history during and after the

Little Ice Age. Noting his results are consistent with "research on various glaciers of the northern and southern hemisphere [which] has shown that most of them started their retreat in the mid-18th century, thereby indicating the end of the Little Ice Age maximum," he suggests this pattern of deglaciation may be a global phenomenon.

- Copland *et al.* (2011) used a combination of previously published literature and repeat satellite imagery to catalog ice behavior in the Karakoram since 1961. They found "there has been a marked increase in the recent occurrence of glacier surging in the Karakoram" associated with "a significant increase in winter, summer, and annual precipitation in the Karakoram over the period 1961–1999." In particular, there has been "a doubling in the number of new surges in the 14 years after 1990 (26 surges) than in the 14 years before 1990 (13 surges)." This increase in glacier surging correlates with the positive mass balances reported for the Karakoram by Gardelle *et al.* (2011) and others over the past few decades and is consistent with the many other glaciological indicators of recent ice stability or expansion in this area reported by Hewitt (2005), Pecci and Smiraglia (2000), Mayer *et al.* (2006), and Quincey *et al.* (2009).

- In their review of glacial activity in the Garhwal Himalaya, Bali *et al.* (2011) report the Gangotri Glacier, which was earlier receding at a rate of around 26 m/year between 1935 and 1971 (Raina, 2003; Sharma and Owen, 1996; Naithani *et al.*, 2001; Srivastava, 2003), has more recently shown a gradual decline in rate of recession, falling to 17 m/year for 1974–2004 and 12 m/year for 2004–2005 (Kumar *et al.*, 2008). The Dokriana Glacier maintained an overall constant rate of recession (around 16–18 m/year) between the years 1962 and 1995 (Dobhal *et al.*, 2004). The recession of the Pindari Glacier diminished from about 26 m/year for 1845–1906 to about 6.5 m/year in 1966–2007 (Bali *et al.*, 2009), and the Milam Glacier has exhibited a steady rate of recession of around 16.5 m/year over the past 150 years (Shukla and Siddiqui, 2001). The terminus of the Donagiri Glacier has exhibited intermittent recession and advance (Srivastava and Swaroop, 2001; Swaroop *et al.*, 2001), and the Satopanth Glacier, which earlier had been receding at the rate of 22.86 m/year, showed a recession rate of 6.5 m/year during 2005–2006 (Ganjoo and Koul, 2009). Most conspicuously, the 70-km-long Siachin glacier "has been standing steady for the last several decades," exhibiting an almost stable terminus that receded by only 8–10 m in 1995–2008 (Ganjoo and Koul, 2009)

Observations: The Cryosphere

and showing signs of advancement during the last decade (Sinha and Shah, 2008).

- Azam *et al.* (2012) describe recent glaciological changes in the western Himalaya using mass balance and surface ice flow velocity measurements made in 2002–2010 on the Chhota Shigri Glacier in the Pir Panjal Range, which they compare with similar data collected in 1987–1989. They find “the glacier has experienced a period of near-zero or slightly positive mass balance in the 1990s ... [before] ... starting to shrink at the beginning of the 21st century,” with only a small change in position of the terminus between 1988 and 2010.

Noting the Chhota Shigri seems to be representative of other glaciers in the Pir Panjal range (Berthier *et al.*, 2007), Azam *et al.* conclude many Western Himalayan glaciers may have experienced growth rather than shrinkage during the last 10–12 years of the twentieth century. The authors note “this result challenges the generally accepted idea that glaciers in the Western Himalaya have been shrinking rapidly for the last few decades” as, for example, implied by Solomon *et al.* (2012) in the IPCC’s *Fourth Assessment Report*.

- Hewitt (2005) noted the west end of the Himalayan arc, where China, India, and Pakistan meet, was characterized by a recent anomalous gain of mass by Karakoram glaciers. This feature was referred to in subsequent studies by Zemp *et al.* (2009), Cogley (2011), and Scherler *et al.* (2011), becoming known as the “Karakoram anomaly.”

Noting the paucity of data on the Karakoram, Gardelle *et al.* (2012) set out to calculate a regional mass balance for glaciers in the central Karakoram for 1999–2008 based on differences between two sets of digital elevation data, one from the February 2000 Shuttle Radar Topographic Mission (SRTM) and the other from the December 2008 optical stereo imagery acquired by the Satellite Pour l’Observation de la Terre (SPOT5) program. Gardelle *et al.* (2012) report the presence of “a highly heterogeneous spatial pattern of changes in glacier elevation, which shows that ice thinning and ablation at high rates can occur on debris-covered glacier tongues,” and which results in “the regional mass balance [being] just positive at $+0.11 \pm 0.22$ m/year water equivalent.” Glacier expansion or speed-up consistent with this result has been previously reported by Hewitt (2005), Quincey *et al.* (2009), and Heid and Kaab (2011).

- In other research, “more than 50% of Karakoram glaciers were advancing or stable between 2000 and 2008” (Scherler *et al.*, 2011), and Fuita and Nuimura

(2011) reported a descending trend in the modeled equilibrium-line altitude in the Karakoram during 1976–1995. Fowler and Archer (2006) reported an increase in winter precipitation since 1961, a potential source for greater accumulation in the upper parts of glaciers (Hewitt, 2005; Quincey *et al.* 2009, 2011). Between 1961 and 2000, Fowler and Archer report, mean summer temperature declined at all climate stations in the region, probably resulting in a decreasing glacier melt.

Conclusions

In its *Fourth Assessment Report*, the IPCC wrote the likelihood of India’s western Himalayan glaciers “disappearing by the year 2035 or perhaps sooner is very high if the Earth keeps warming at the current rate” (Solomon *et al.*, 2007). Given the obvious importance of the Himalayan glaciers as water sources for the populous downstream lowlands of south Asia, this was an alarming scenario to promulgate, and Cogley *et al.* (2010) give an account of how this misinformation came to be adopted.

Shroder *et al.* (2000) had discovered an absence of rapid Himalayan melting some time before, during their fieldwork in 1993–1995, from which they state “the glacial fed rivers are thus not going to die an immediate death.” They pointed out “even if a time comes that there are no glaciers around, the rivers will still flow” because at the foothills the contribution of glacial melt water is only 10 to 15 percent of the total, the rest being supplied by rain and ground water.

Real-world empirical data are needed to test alarmist speculations about the disappearance of Himalayan glaciers. Byers (2007), Zemp and Haeberli (2007), and Kumar *et al.* (2008) all point out the Himalayan glacier response to climate change is poorly known, mainly because of the lack of long-term and continuous records of glacial fluctuations at sites throughout the mountain chain.

The research studies summarized above are beginning to provide the factual data required to improve our understanding of how Himalayan glaciers might respond to climate change. The beliefs of Solomon *et al.* (2007) are now more open to observational testing, and we no longer have to rely on speculative computer modeling projections.

Two main lines of empirical argument bear on the issue. The first, after Chaujar (2009), is based upon viewing twentieth century glacial change in the context of the post-LIA climatic warming that started in the 1860s and caused glacier shrinkages around the world, including in the Himalayas. As Chaujar notes, these changes started “long before the historical

increase in the air's CO₂ content could have been involved in the process of their retreat." Hence, there is no reason to believe the late twentieth century warming, and glacial shrinkage where it occurred, were anything more than a continuation of the nonanthropogenic return of Earth from the frigid depths of the Little Ice Age.

The second argument is based on the growing number of local and regional studies becoming available from throughout the Himalayas. Though variability in ice-mass change exists from place to place, most recent studies have found the glaciers of the Indian subcontinent "are receding at a much slower pace in comparison to what they were about a few decades back" (Bali *et al.*, 2011; see also Yadav, *et al.*, 2004), or even growing in places in the Karakoram, Hindu Kush, and Western Himalayan ranges. This glacial growth appears to be driven "by a quirk of the atmospheric general circulation that is not understood"; "more snow is being delivered to the mountain range at present, and less heat" (Cogley, 2012). Gardelle *et al.* (2012) have provided strong evidence for the existence of an increasing ice mass balance in the Karakoram region, and Copland *et al.* (2011) stress that contrary to what is often claimed about many of Earth's mountain glaciers, "it is evident that glacier surging is more extensive than previously reported in the Karakoram and that the number of glacier surges has increased recently," driven by positive mass balances.

References

- Azam, M.F., Wagon, P., Ramanathan, A., Vincent, C., Sharma, P., Arnaud, Y., Linda, A., Pottakkal, J.G., Bali, R., Agarwal, K.K., Ali, S.N., Rastogi, S.K., and Krishna, K. 2009. Monitoring recession pattern of Central Himalayan Glaciers: some optimistic observations. *Proceedings of the Indian Science Congress* **96**: 79–80.
- Bali, R., Agarwal, K.K., Ali, S.N., and Srivastava, P. 2011. Is the recession pattern of Himalayan glaciers suggestive of anthropogenically induced global warming? *Arabian Journal of Geosciences* **4**: 1087–1093.
- Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagon, P., and Chevallier, P. 2007. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing of Environment* **108**: 327–338.
- Byers, A.C. 2007. An assessment of contemporary glacier fluctuations in Nepal's Khumbu Himal using repeat photography. *Himalayan Journal of Sciences* **4**: 21–26.
- Chaujar, R.K. 2009. Climate change and its impact on the Himalayan glaciers—a case study on the Chorabari glacier, Garhwal Himalaya, India. *Current Science* **96**: 703–708.
- Cogley, J.G. 2011. Present and future states of Himalaya and Karakoram glaciers. *Annals of Glaciology* **52**: 69–73.
- Cogley, G. 2012. No ice lost in the Karakoram. *Nature Geoscience* **5**: 305–306.
- Cogley, J.G., Kargel, J.S., Kaser, G., and Van der Veen, C.J. 2010. Tracking the source of glacier misinformation. *Science* **327**: 522.
- Copland, L., Sylvestre, T., Bishop, M.P., Shroder, J.F., Seong, Y.B., Owen, L.A., Bush, A., and Kamp, U. 2011. Expanded and recently increased glacier surging in the Karakoram. *Arctic, Antarctic, and Alpine Research* **43**: 503–516.
- Dobhal, D.P., Gergan, J.T., and Thayyen, R.J. 2004. Recession and morphogeometrical changes of Dokriani glacier (1962–1995) Garhwal Himalaya, India. *Current Science* **86**: 692–696.
- Fowler, H.J. and Archer, D.R. 2006. Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate* **19**: 4276–4293.
- Fujita, K. and Nuimura, T. 2011. Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences USA* **108**: 14,011–14,014.
- Ganjoo, R.K. and Koul, M.N. Is the Siachen glacier melting? *Current Science* **97**: 309–310.
- Gardelle, J., Berthier, E., and Arnaud, Y. 2012. Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience* **5**: 322–325.
- Heid, T. and Kaab, K. 2011. Worldwide widespread decadal-scale decrease of glaciers speed revealed using repeat optical satellite images. *Cryosphere Discussions* **5**: 3025–3051.
- Hewitt, K. 2005. The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya. *Mountain Research and Development* **25**: 332–340.
- Kumar, K., Dumka, R.K., Miral, M.S., Satyal, G.S., and Pant, M. 2008. Estimation of retreat rate of Gangotri glacier using rapid static and kinematic GPS survey. *Current Science* **94**: 258–262.
- Mayer, C., Lambrecht, A., Belo, M., Smiraglia, C., and Diolaiuti, G. 2006. Glaciological characteristics of the ablation zone of Baltoro glacier, Karakoram, Pakistan. *Annals of Glaciology* **43**: 123–131.
- Naithani, A.K., Nainwal, H.C., and Prasad, C.P. 2001. Geomorphological evidences of retreat of Gangotri glacier and its characteristics. *Current Science* **80**: 87–94.

Observations: The Cryosphere

- Pecci, M. and Smiraglia, C. 2000. Advance and retreat phases of the Karakorum glaciers during the 20th century: case studies in Braldo Valley (Pakistan). *Geografia Fisica e Dinamica Quaternaria* **23**: 73–85.
- Quincey, D.J., Braun, M., Glasser, N.F., Bishop, M.P., Hewitt, K., and Luckman, A. 2011. Karakoram glacier surge dynamics. *Geophysical Research Letters* **38**: 10.1029/2011GL049004.
- Quincey, D.J., Copland, L., Mayer, C., Bishop, M.P., Luckman, A.M., and Bel, M. 2009. Ice velocity and climate variations for Baltoro Glacier, Pakistan. *Journal of Glaciology* **55**: 1061–1071.
- Raina, V.K. 2003. History of Gangotri glacier down the ages. In: Proceedings of Workshop on Gangotri Glacier, 2003. *Geological Survey of India, Special Publication* **80**: 1–10.
- Raina, V.K. 2006. *Glaciers: The Rivers of Ice*. Geological Society of India.
- Scherler, D., Bookhagen, B., and Strecker, M.R. 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience* **4**: 156–159.
- Schmidt, S. and Nusser, M. 2009. Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan. *Journal of Glaciology* **55**: 949–959.
- Sharma, M.C. and Owen, L.A. 1996. Quaternary glacial history of NW Garhwal, Central Himalaya. *Quaternary Science Reviews* **15**: 335–365.
- Shroder, J.F., Bishop, M.P., Copland, L., and Sloan, V.F. 2000. Debris-covered glaciers and rock glaciers in the Nanga Parbat Himalaya, Pakistan. *Geografiska Annaler* **82A**: 17–31.
- Shukla, S.P. and Siddiqui, M.A. 2001. Recession of the snout front of Milam glacier, Goriganga valley, Pithoragarh district, Uttar Pradesh. *Geological Survey of India, Special Publication* **53**: 71–75.
- Sinha, L.K. and Shah, A. 2008. Temporal analysis of Siachen Glacier: a remote sensing perspective. *National Seminar, Glacial Geomorphology and Paleoglaciation in Himalaya*, pp. 43–44.
- Solomon, S., Qin, D., Manning, M., Chen Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.). 2007. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, Cambridge, United Kingdom, and New York, New York, USA.
- Srivastava, D. 2003. Recession of Gangotri glacier. Proceedings of the Workshop on Gangotri Glacier, 2003. *Geological Survey of India, Special Publication* **80**: 21–30.
- Srivastava, D. and Swaroop, S. 2001. Oscillations of snout of Dunagiri glacier. *Geological Survey of India, Special Publication* **53**: 83–85.
- Swaroop, S., Oberoi, L.K., Srivastava, D., and Gautam, C.K. 2001. Recent fluctuations in the snout of Dunagiri and Chaurabari glacier, Dhauliganga and Mandakini-Alaknanda basins, Chamoli district, Uttar Pradesh. *Geological Survey of India, Special Publication* **53**: 77–81.
- Yadav, R.R., Park, W.-K., Singh, J., and Dubey, G. 2004. Do the western Himalayas defy global warming? *Geophysical Research Letters* **31**: 10.1029/2004GL020201.
- Zemp, M. and Haeberli, W. 2007. Glaciers and ice caps. In: Eamer, J. (Ed.). *Global Outlook for Ice and Snow*. United Nations Environment Programme, Nairobi, pp. 115–152.
- Zemp, M., Hoelzle, M., and Haeberli, W. 2009. Six decades of glacier mass-balance observations: A review of the worldwide monitoring network. *Annals of Glaciology* **50**: 101–111.

5.9.4 African Glaciers

African montane glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights; i.e. on large mountains. One of these, Kenya's Mt. Kilimanjaro, has achieved iconic status because of Ernest Hemingway's famous short story "The Snows of Kilimanjaro."

During the 1980s and 1990s, U.S. politicians Al Gore, John McCain, and Hilary Clinton, together with other public figures around the world, made emotional statements in support of reducing human-related CO₂, based on their (incorrect) understanding that Kilimanjaro's summit ice field was melting under the influence of anthropogenic global warming. Acknowledging subsequent research, Justice Michael Burton in his 2007 U.K. High Court judgement against Mr. Gore's film, *An Inconvenient Truth*, concluded such views are in error. Modern glacier recession on Kilimanjaro began around 1880, which rules out post-1950 human emissions as the primary cause, despite that belief being encouraged by scattered scientific reports (Alverson *et al.*, 2001; Irion, 2001; Thompson *et al.*, 2002). This oversimplified view is wrong, as shown in the following papers.

- Molg *et al.* (2003a) note all three glacier-bearing volcanic mountains in East Africa—Kilimanjaro (Tanzania, Kenya), Mount Kenya (Kenya), and Rwenzori (Zaire, Uganda)—have experienced strong

ice field recession over the past century or so. They also report, after Hastenrath (2001), “there is no evidence of a sudden change in temperature [in East Africa] at the end of the 19th century,” as confirmed by King’uyu *et al.* (2000) and Hay *et al.* (2002), who show East African twentieth century temperature records show diverse trends and do not exhibit a uniform warming signal.

- Georges and Kaser (2002) report on an automatic weather station installed in 2002 on a horizontal glacier surface at the Kilimanjaro Northern Icefield. Since then, monthly mean air temperatures have varied only slightly around the annual mean of -7.1°C , and air temperatures have never risen above freezing. It is difficult to understand how ice could melt under such conditions.

- Molg and Hardy (2004) used data from this weather station to derive an energy balance for the Kibo summit icefield on Mt. Kilimanjaro. They discovered “the main energy exchange at the glacier-atmosphere interface results from the terms accounting for net radiation, governed by the variation in net shortwave radiation,” which is controlled by surface albedo (and thus precipitation variability), which determines the reflective characteristics of the glacier’s surface. Much less significant, according to the two researchers, is the temperature-driven turbulent exchange of sensible heat, which they say “remains considerably smaller and of little importance.” Molg and Hardy conclude “modern glacier retreat on Kilimanjaro and in East Africa in general [was] initiated by a drastic reduction in precipitation at the end of the 19th century (Hastenrath, 1984, 2001; Kaser *et al.*, 2004),” and reduced accumulation and increased ablation have “maintained the retreat until the present (Molg *et al.*, 2003a).”

- Molg *et al.* (2003b) applied a radiation model to an idealized representation of the 1880 icecap of Kilimanjaro, concluding “modern glacier retreat on Kilimanjaro is much more complex than simply attributable to ‘global warming only.’” Instead, and as reported by many other authors, the ice retreat has been “a process driven by a complex combination of changes in several different climatic parameters [e.g., Kruss, 1983; Kruss and Hastenrath, 1987; Hastenrath and Kruss, 1992; Kaser and Georges, 1997; Wagnon *et al.*, 2001; Kaser and Osmaston, 2002; Francou *et al.*, 2003; Molg *et al.*, 2003b], with humidity-related variables dominating this combination.”

- Cullen *et al.* (2006) report “all ice bodies on Kilimanjaro have retreated drastically between 1912–

2003,” but they add the highest glacial recession rates on Kilimanjaro “occurred in the first part of the twentieth century, with the most recent retreat rates (1989–2003) smaller than in any other interval.” In addition, they say no temperature trends over the period 1948–2005 have been observed at the approximate height of the Kilimanjaro glaciers, but there has been a small decrease in the region’s specific humidity over this period.

In terms of why glacier retreat on Kilimanjaro was so dramatic over the twentieth century, the six researchers note for the mountain’s plateau glaciers, there is no alternative for them “other than to continuously retreat once their vertical margins are exposed to solar radiation,” which appears to have happened sometime in the latter part of the nineteenth century. They also report the “vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in 20th century climate have not altered their continuous demise.” Consequently, the twentieth century retreat of Kilimanjaro’s plateau glaciers is a long-term response to what we could call “relict climate change” that likely occurred in the late nineteenth century.

In the case of the mountain’s slope glaciers, Cullen *et al.* say their rapid recession in the first part of the twentieth century shows they “were drastically out of equilibrium,” which they take as evidence the glaciers “were responding to a large prior shift in climate.” In addition, they report “no footprint of multidecadal changes in areal extent of slope glaciers to fluctuations in twentieth century climate is observed, but their ongoing demise does suggest they are still out of equilibrium,” and in this regard they add their continuing but decelerating demise could be helped along by the continuous slow decline in the air’s specific humidity. Cullen *et al.* confidently conclude the glaciers of Kilimanjaro “are merely remnants of a past climate rather than sensitive indicators of 20th century climate change.”

- Two additional studies, by Mote and Kaser (2007) and Duane *et al.* (2008), reject the temperature-induced decline hypothesis for Kilimanjaro. Duane *et al.* conclude “the reasons for the rapid decline in Kilimanjaro’s glaciers are not primarily due to increased air temperatures, but a lack of precipitation,” and Mote and Kaser report “warming fails spectacularly to explain the behavior of the glaciers and plateau ice on Africa’s Kilimanjaro massif ... and to a lesser extent other tropical glaciers.”

- What, then, caused the ice fields of Kilimanjaro to recede steadily for so many years? Citing

Observations: The Cryosphere

“historical accounts of lake levels (Hastenrath, 1984; Nicholson and Yin, 2001), wind and current observations in the Indian Ocean and their relationship to East African rainfall (Hastenrath, 2001), water balance models of lakes (Nicholson and Yin, 2001), and paleolimnological data (Verschuren *et al.*, 2000),” Molg *et al.* (2003a, b) say “all data indicate that modern East African climate experienced an abrupt and marked drop in air humidity around 1880,” and the resultant “strong reduction in precipitation at the end of the 19th century is the main reason for modern glacier recession in East Africa,” as it considerably reduces glacier mass balance accumulation, as demonstrated for the region by Kruss (1983) and Hastenrath (1984). In addition, they note “increased incoming shortwave radiation due to decreases in cloudiness—both effects of the drier climatic conditions—plays a decisive role for glacier retreat by increasing ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Molg *et al.*, 2003a).”

- Kaser *et al.* (2004) conclude all relevant “observations and facts” clearly indicate “climatological processes other than air temperature control the ice recession in a direct manner” on Kilimanjaro, and “positive air temperatures have not contributed to the recession process on the summit.” Those conclusions directly contradict Irion (2002) and Thompson *et al.* (2002), who see the recession of Kilimanjaro’s glaciers as a direct consequence solely of increased air temperature.

Conclusions

In support of the findings of Molg *et al.* (2003a, b), for Africa, analyses of glacier retreat throughout the tropics uniformly suggest that changes in air humidity have been dominant in controlling modern retreat where it has occurred [e.g., Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al.* (2003) for the Bolivian Cordillera Real (both South American Andes); Kruss (1983), Kruss and Hastenrath (1987), and Hastenrath (1995) for Mount Kenya (East Africa); and Molg *et al.* (2003a) for the Rwenzori massif (East Africa)].

Kaser *et al.* (2004) conclude “changes in air humidity and atmospheric moisture content (e.g. Soden and Schroeder, 2000) seem to play an underestimated key role in tropical high-mountain climate (Broecker, 1997).” Regarding East African montane glaciers, it is important to remember “the dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser

and Noggler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Molg *et al.*, 2003b).” These factors are related to a drying of the regional atmosphere that commenced around 1880 and lasted through the twentieth century.

We conclude warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

References

- Alverson, K., Bradley, R., Briffa, K., Cole, J., Hughes, M., Larocque, I., Pedersen, T., Thompson, L.G., and Tudhope, S. 2001. A global paleoclimate observing system. *Science* **293**: 47–49.
- Broecker, W.S. 1997. Mountain glaciers: records of atmospheric water vapor content? *Global Biogeochemical Cycles* **4**: 589–597.
- Cullen, N.J., Molg, T., Kaser, G., Hussein, K., Steffen, K., and Hardy, D.R. 2006. Kilimanjaro glaciers: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters* **33**: 10.1029/2006GL027084.
- Duane, W.J., Pepin, N.C., Losleben, M.L., and Hardy, D.R. 2008. General characteristics of temperature and humidity variability on Kilimanjaro, Tanzania. *Arctic, Antarctic, and Alpine Research* **40**: 323–334.
- Francou, B., Vuille, M., Wagon, P., Mendoza, J., and Sicart, J.E. 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16°S. *Journal of Geophysical Research* **108**: 10.1029/2002JD002473.
- Georges, C. and Kaser, G. 2002. Ventilated and unventilated air temperature measurements for glacier-climate studies on a tropical high mountain site. *Journal of Geophysical Research* **107**: 10.1029/2002JD002503.
- Hastenrath, S. 1984. *The Glaciers of Equatorial East Africa*. D. Reidel, Norwell, MA, USA.
- Hastenrath, S. 1995. Glacier recession on Mount Kenya in the context of the global tropics. *Bulletin de l’Institut Français d’Etudes Andines* **24**: 633–638.
- Hastenrath, S. 2001. Variations of East African climate during the past two centuries. *Climatic Change* **50**: 209–217.
- Hastenrath, S. and Kruss, P.D. 1992. The dramatic retreat of Mount Kenya’s glaciers between 1963 and 1987: Greenhouse forcing. *Annals of Glaciology* **16**: 127–133.
- Hay, S.I., Cox, J., Rogers, D.J., Randolph, S.E., Stern, D.I., Shanks, G.D., Myers, M.F., and Snow, R.W. 2002. Climate

change and the resurgence of malaria in the East African highlands. *Nature* **415**: 905–909.

Irion, R. 2001. The melting snows of Kilimanjaro. *Science* **291**: 1690–1691.

Kaser, G. and Georges, C. 1997. Changes in the equilibrium line altitude in the tropical Cordillera Blanca (Peru) between 1930 and 1950 and their spatial variations. *Annals of Glaciology* **24**: 344–349.

Kaser, G., Hardy, D.R., Molg, T., Bradley, R.S., and Hyera, T.M. 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *International Journal of Climatology* **24**: 329–339.

Kaser, G. and Noggler, B. 1996. Glacier fluctuations in the Rwenzori Range (East Africa) during the 20th century—a preliminary report. *Zeitschrift für Gletscherkunde und Glazialgeologie* **32**: 109–117.

Kaser, G. and Osmaston, H. 2002. *Tropical Glaciers*. Cambridge University Press, Cambridge, UK.

King'uyu, S.M., Ogallo, L.A., and Anyamba, E.K. 2000. Recent trends of minimum and maximum surface temperatures over Eastern Africa. *Journal of Climate* **13**: 2876–2886.

Kruss, P.D. 1983. Climate change in East Africa: a numerical simulation from the 100 years of terminus record at Lewis Glacier, Mount Kenya. *Zeitschrift für Gletscherkunde und Glazialgeologie* **19**: 43–60.

Kruss, P.D. and Hastenrath, S. 1987. The role of radiation geometry in the climate response of Mount Kenya's glaciers, part 1: Horizontal reference surfaces. *International Journal of Climatology* **7**: 493–505.

Molg, T., Georges, C., and Kaser, G. 2003a. The contribution of increased incoming shortwave radiation to the retreat of the Rwenzori Glaciers, East Africa, during the 20th century. *International Journal of Climatology* **23**: 291–303.

Molg, T. and Hardy, D.R. 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research* **109**: 10.1029/2003JD004338.

Molg, T., Hardy, D.R., and Kaser, G. 2003b. Solar-radiation-maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *Journal of Geophysical Research* **108**: 10.1029/2003JD003546.

Mote, P.W. and Kaser, G. 2007. The shrinking glaciers of Kilimanjaro: Can global warming be blamed? *American Scientist* **95**: 318–325.

Nicholson, S.E. and Yin, X. 2001. Rainfall conditions in Equatorial East Africa during the nineteenth century as

inferred from the record of Lake Victoria. *Climatic Change* **48**: 387–398.

Soden, B.J. and Schroeder, S.R. 2000. Decadal variations in tropical water vapor: a comparison of observations and a model simulation. *Journal of Climate* **13**: 3337–3341.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotto, T.A., Lin, P.-N., Mikhalevko, V.N., Hardy, D.R., and Beer, J. 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* **298**: 589–593.

Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

Wagon, P., Ribstein, P., Francou, B., and Sicart, J.E. 2001. Anomalous heat and mass budget of Glaciar Zongo, Bolivia, during the 1997/98 El Niño year. *Journal of Glaciology* **47**: 21–28.

5.9.5 South America

Studies of alpine glaciers from South America fail to provide evidence for widespread or uniform glacial retreat under the influence of modern global warming.

- Harrison and Winchester (2000) used dendrochronology, lichenometry, and aerial photography to date nineteenth and twentieth century fluctuations of the Arco, Colonia, and Arenales glaciers on the eastern side of the Hielo Patagonico Norte in southern Chile. These glaciers, together with four others on the western side of the ice field, began to retreat from their Little Ice Age maximum positions between 1850 and 1880. The trend of retreat continued “through the first half of the 20th century with various still-stands and oscillations between 1925 and 1960 ... with retreat increasing since the 1960s,” as also has been observed at many Northern Hemisphere sites.

- Glasser *et al.* (2004) describe glacial fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte and the Hielo Patagonico Sur. The evidence indicates glacial advance and retreat since about 6,000 ¹⁴C years BP in concert with the known Roman Warm Period, cold Dark Ages, warm Medieval Warm Period, cold Little Ice Age and twentieth century warming. A similar pattern of glacial activity occurred to the east of the Hielo Patagonico Sur, in the Rio Guanaco region of the Precordillera. Here, Wenzens (1999) detected five distinct periods of glacial advancement: “4500–4200, 3600–3300, 2300–2000, 1300–1000 ¹⁴C years BP and AD 1600–1850.” The glacial advancements during

Observations: The Cryosphere

the cold interval prior to the Roman Warm Period constitute “part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al.*, 1998; Wasson and Claussen, 2002). This period coincided with the abrupt decrease in solar activity that led van Geel *et al.* (2000) to stress the importance of solar irradiance as a driver for climate variation.

Glacial histories similar to those of Patagonia have been described from geomorphological moraine analysis recorded from other parts of southern Chile (e.g., Kuylensstierna *et al.*, 1996; Koch and Kilian, 2001), the Peruvian Cordillera Blanca (Kaser and Georges, 1997), and the Bolivian Cordillera Real (Francou *et al.*, 2003). Further afield, similar histories are also known from areas peripheral to the North Atlantic and in central Asia (cf. Grove, 1988; Savoskul, 1997).

- Georges (2004) constructed a twentieth century history of glacial fluctuations in the Cordillera Blanca of Peru, the largest glaciated area in the tropics. Glacier recession of unknown extent occurred early in the century, followed by a marked readvance in the 1920s that nearly reached the Little Ice Age maximum. Thereafter came a very strong glacial mass shrinkage in the 1930s–1940s, quiescence, and an intermediate retreat from the mid-1970s until the end of the century. Georges comments, “the intensity of the 1930s–1940s retreat was more pronounced than that of the one at the end of the century,” the data indicating the rate of wastage in the 1930s–1940s was twice as great as that of the last two decades of the twentieth century. The advances in the Cordillera Blanca in the late 1920s were almost as great as those experienced there during the Little Ice Age.

- Koch and Kilian (2005) used dendrochronology to map and date the moraine systems of Glaciar Lengua and neighboring glaciers of Gran Campo Nevado in the southernmost Andes of Chile. They found the culmination of the Little Ice Age glacial advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Rothlisberger, 1986; Aniya, 1996), but glaciers at Hielo Patagonico Norte and Hielo Patagonico Sur also formed prominent moraines around 1870 and 1880 (Warren and Sugden, 1993; Winchester *et al.*, 2001; Luckman and Villalba, 2001).

- Polissar *et al.* (2006) used two 1,500-yr-long sediment cores from Lakes Mucubaji and Blanca, Venezuela, to reconstruct proxy records for glacier activity, temperature, and moisture balance in that part of the tropical Andes (the Cordillera de Merida). Techniques used included measurement for biogenic

silica, magnetic susceptibility, total organic carbon (TOC), total nitrogen (TN), $\delta^{13}\text{CTOC}$, $\delta^{15}\text{NTN}$, and C/N.

Polissar *et al.* note the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and $\delta^{14}\text{C}$ measurements; spectral analysis identifies significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, which match the de Vries and Gleissberg oscillations known from solar irradiance reconstructions; and the magnetic susceptibility record follows the solar-irradiance reconstruction during 1520–1650 but is not correlated with solar and volcanic forcings during that time. The four glacial advances that occurred between AD 1250 and 1810 coincide with solar-activity minima and also with temperature declines of $-3.2 \pm 1.4^\circ\text{C}$ and precipitation increases of $\sim +20\%$.

Conclusions

These South American studies make clear the strong correlation between glacial advance and retreat and the warmings and coolings of the past several centuries. Moreover, independent evidence for solar control, including at the shorter de Vries (~ 208 yr) and Gleissberg (~ 80 yr) wavelengths, is provided by Polissar *et al.*'s work in Venezuela.

Most of the observed glacial cycles date from long before a time when human CO_2 emissions could have been a cause. In addition, CO_2 levels lower than those of the twentieth century occurred during older warm intervals, and no unusual glacial retreats occurred during the mild twentieth century warming.

References

- Aniya, M. 1996. Holocene variations of Ameghino Glacier, southern Patagonia. *The Holocene* **6**: 247–252.
- Francou, B., Vuille, M., Wagnon, P., Mendoza, J., and Sicart, J.E. 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16°S . *Journal of Geophysical Research* **108**: 10.1029/2002JD002473.
- Georges, C. 2004. 20th-century glacier fluctuations in the tropical Cordillera Blanca, Peru. *Arctic, Antarctic, and Alpine Research* **35**: 100–107.
- Glasser, N.F., Harrison, S., Winchester, V., and Aniya, M. 2004. Late Pleistocene and Holocene palaeoclimate and glacier fluctuations in Patagonia. *Global and Planetary Change* **43**: 79–101.
- Grosjean, M., Geyh, M.A., Messerli, B., Schreier, H., and Veit, H. 1998. A late-Holocene (2600 BP) glacial advance

in the south-central Andes (29°S), northern Chile. *The Holocene* **8**: 473–479.

Grove, J.M. 1988. *The Little Ice Age*. Routledge, London, UK.

Harrison, S. and Winchester, V. 2000. Nineteenth- and twentieth-century glacier fluctuations and climatic implications in the Arco and Colonia Valleys, Hielo Patagonico Norte, Chile. *Arctic, Antarctic, and Alpine Research* **32**: 55–63.

Kaser, G. and Georges, C. 1997. Changes in the equilibrium line altitude in the tropical Cordillera Blanca (Peru) between 1930 and 1950 and their spatial variations. *Annals of Glaciology* **24**: 344–349.

Koch, J. and Kilian, R. 2005. “Little Ice Age” glacier fluctuations, Gran Campo Nevado, southernmost Chile. *The Holocene* **15**: 20–28.

Koch, J. and Kilian, R. 2001. Dendroglaciological evidence of Little Ice Age glacier fluctuations at the Gran Campo Nevado, southernmost Chile. In: Kaennel Dobbertin, M. and Braker, O.U. (Eds.) *International Conference on Tree Rings and People*. Davos, Switzerland, p. 12.

Kuylensstierna, J.L., Rosqvist, G.C., and Holmlund, P. 1996. Late-Holocene glacier variations in the Cordillera Darwin, Tierra del Fuego, Chile. *The Holocene* **6**: 353–358.

Luckman, B.H. and Villalba, R. 2001. Assessing the synchronicity of glacier fluctuations in the western Cordillera of the Americas during the last millennium. In: Markgraf, V. (Ed.), *Interhemispheric Climate Linkages*. Academic Press, New York, NY, USA, pp. 119–140.

Mercer, J.H. 1970. Variations of some Patagonian glaciers since the Late-Glacial: II. *American Journal of Science* **269**: 1–25.

Polissar, P.J., Abbott, M.B., Wolfe, A.P., Bezada, M., Rull, V., and Bradley, R.S. 2006. Solar modulation of Little Ice Age climate in the tropical Andes. *Proceedings of the National Academy of Sciences USA* **103**: 8937–8942.

Rothlisberger, F. 1986. *10 000 Jahre Gletschergeschichte der Erde*. Verlag Sauerlander, Aarau.

Savoskul, O.S. 1997. Modern and Little Ice Age glaciers in “humid” and “arid” areas of the Tien Shan, Central Asia: two different patterns of fluctuation. *Annals of Glaciology* **24**: 142–147.

van Geel, B., Heusser, C.J., Renssen, H., and Schuurmans, C.J.E. 2000. Climatic change in Chile at around 2700 B.P. and global evidence for solar forcing: a hypothesis. *The Holocene* **10**: 659–664.

Warren, C.R. and Sugden, D.E. 1993. The Patagonian icefields: a glaciological review. *Arctic and Alpine Research* **25**: 316–331.

Wasson, R.J. and Claussen, M. 2002. Earth systems models: a test using the mid-Holocene in the Southern Hemisphere. *Quaternary Science Reviews* **21**: 819–824.

Wenzens, G. 1999. Fluctuations of outlet and valley glaciers in the southern Andes (Argentina) during the past 13,000 years. *Quaternary Research* **51**: 238–247.

Winchester, V., Harrison, S., and Warren, C.R. 2001. Recent retreat Glacier Nef, Chilean Patagonia, dated by lichenometry and dendrochronology. *Arctic, Antarctic and Alpine Research* **33**: 266–273.

5.9.6 North America

The history of North American glacial activity fails to support the claim that anthropogenic CO₂ emissions are causing glaciers to melt. Relevant studies include the following.

- Dowdeswell *et al.* (1997) analyzed the mass balance histories of the 18 Arctic glaciers with the longest observational records, finding that just over 80 percent of them displayed negative mass balances over the last half of the twentieth century. However, they note “ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age.” They conclude “there is no compelling indication of increasingly negative balance conditions which might, a priori, be expected from anthropogenically induced global warming.”
- Calkin *et al.* (2001) reviewed current research on Holocene neoglaciations along the Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where several periods of glacial advance and retreat have occurred during the past 7,000 years. Over the younger part of this record, a general glacial retreat occurred during the Medieval Warm Period prior to AD 1200, after which three major advances occurred during the Little Ice Age: in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century. During these three cold intervals, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers also “reached their Holocene maximum extensions.”
- Clague *et al.* (2004) documented glacier and vegetation changes at high elevations in the upper Bowser River basin in the northern Coast Mountains of British Columbia, based on studies of the distributions of glacial moraines and trimlines, tree-ring data, cores from two small lakes sampled for a variety of analyses (magnetic susceptibility, pollen,

Observations: The Cryosphere

diatoms, chironomids, carbon and nitrogen content, ^{210}Pb , ^{137}Cs , ^{14}C), similar analyses of materials obtained from pits and cores from a nearby fen, and by accelerator mass spectrometry radiocarbon dating of plant fossils, including wood fragments, tree bark, twigs, and conifer needles and cones.

These data provided copious evidence for the occurrence of a glacial advance that began about 3,000 years ago and probably lasted for several hundred years—equivalent to the unnamed cold period prior to the Roman Warm Period that is also known from South America. Evidence also was present for a second phase of glacial activity beginning about 1,300 years ago and which could equate with the Dark Ages Cold Period. A third, and the most extensive and recent, neoglacial interval began shortly after the Medieval Warm Period at about AD 1200 and ended in the late 1800s. Clague *et al.* comment “glaciers achieved their greatest extent of the past 3,000 years and probably the last 10,000 years” during this Little Ice Age period.

- Wiles *et al.* (2004) derived a composite Glacier Expansion Index (GEI) for Alaska based on “dendrochronologically derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens” for three climatically distinct regions—the Arctic Brooks Range, the southern transitional interior straddled by the Wrangell and St. Elias mountain ranges, and the Kenai, Chugach, and St. Elias coastal ranges—after which they compared this history of glacial activity with “the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability” and with the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

Wiles *et al.* discovered “Alaska shows ice expansions approximately every 200 years, compatible with a solar mode of variability,” specifically, the de Vries 208-year solar cycle; by merging this cycle with the cyclical behavior of the PDO, they obtained a dual-parameter forcing function even better correlated with the Alaskan composite GEI, with major glacial advances clearly associated with the Sporer, Maunder, and Dalton solar minima.

Wiles *et al.* said “increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries.” They made no mention of possible CO_2 -induced global warming in discussing their results. Alaskan glacial activity, which in their words “has been shown to be primarily a record of summer

temperature change (Barclay *et al.*, 1999),” appears to be sufficiently well described within the context of centennial (solar) and decadal (PDO) variability superimposed upon the millennial-scale (non- CO_2 -forced) variability that produces longer-lasting Medieval Warm Period and Little Ice Age conditions.

- Pederson *et al.* (2004) used tree-ring reconstructions of North Pacific surface temperature anomalies and summer drought as proxies for winter glacial accumulation and summer ablation, respectively, to create a 300-year history of regional glacial Mass Balance Potential (MBP), which they compared with historic retreats and advances of Glacier Park’s extensively studied Jackson and Agassiz glaciers in northwest Montana.

As they describe it, “the maximum glacial advance of the Little Ice Age coincides with a sustained period of positive MBP that began in the mid-1770s and was interrupted by only one brief ablation phase (~1790s) prior to the 1830s,” after which they report “the mid-19th century retreat of the Jackson and Agassiz glaciers then coincides with a period marked by strong negative MBP.” From about 1850 onward, they note “Carrara and McGimsey (1981) indicate a modest retreat (~3-14 m/yr) for both glaciers until approximately 1917.” At that point, they report, “the MBP shifts to an extreme negative phase that persists for ~25 yr,” during which period the glaciers retreated “at rates of greater than 100 m/yr.”

Continuing with their history, Pederson *et al.* report “from the mid-1940s through the 1970s retreat rates slowed substantially, and several modest advances were documented as the North Pacific transitioned to a cool phase [and] relatively mild summer conditions also prevailed.” From the late 1970s through the 1990s, they say, “instrumental records indicate a shift in the PDO back to warmer conditions resulting in continuous, moderate retreat of the Jackson and Agassiz glaciers.”

- Easterbrook (2010, 2011) described Holocene glacial advances and retreats on Mt. Baker in the North Cascade Range (Washington) that correlate well with the climate changes documented in the Greenland GISP2 ice core and the global temperature curve. Ice margins of Mt. Baker glaciers are shown on air photos dating back to 1943 (see Figure 5.9.6.1) (Easterbrook, 2010, 2011; Harper, 1993). Glaciers that had been retreating since at least the 1920s advanced during the 1947–1977 cool period to positions down-valley from their 1943 termini. They began to retreat once again at the start of the 1977–2007 warm period, and recent termini of the Easton and Boulder glaciers are about 450 m up-valley from

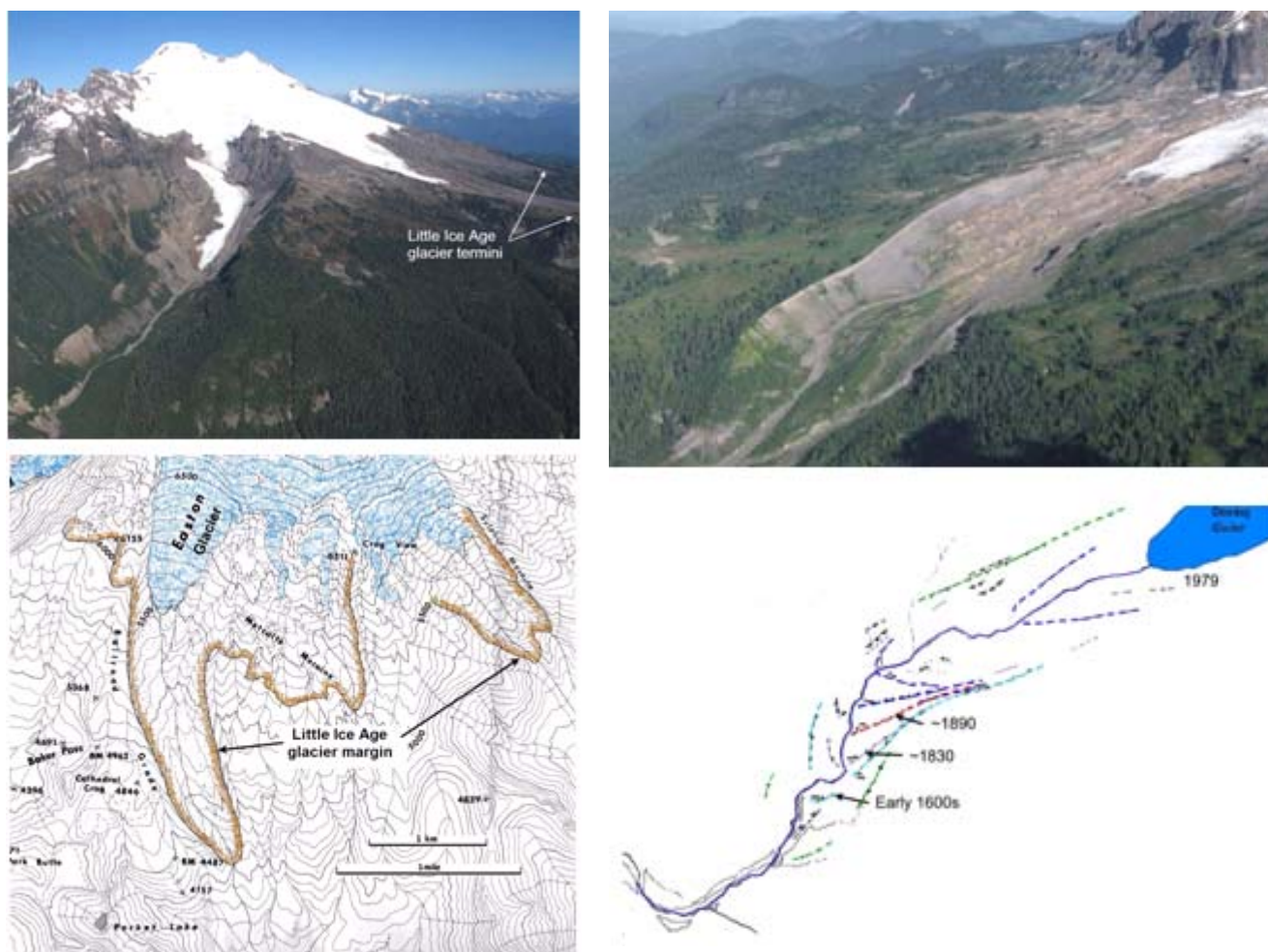


Figure 5.9.6.1. LEFT COLUMN: Photo (upper) and topographic map (lower) of ice retreat from the Little Ice Age maximum, Deming and Easton glaciers, Mt. Baker Washington. RIGHT COLUMN: Photo (upper) and sketch map (lower) of dated moraines down-valley from the Deming glacier on Mt. Baker, Washington. All adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future*. Elsevier, pp. 3–51.

their 1979 positions. These glacial fluctuations closely follow the global temperature record and indicate the warming and cooling cycles seen in the glacial record mimic global climate change. Thus, prehistoric glacial fluctuations also record global climate change.

The glaciers on Mt. Baker show a regular pattern of advance and retreat that matches sea surface temperatures in the nearby northeast Pacific Ocean (the Pacific Decadal Oscillation) (Figure 5.9.6.2), showing the glacier fluctuations occur in parallel with changes in sea surface temperature. Because the glacial record extends back many centuries, it can be used as a proxy for climate change (Figure 5.9.6.3).

- Munroe *et al.* (2012) provide a lacustrine-based Neoglacial record for the glaciers of Montana's

Glacier National Park (GNP), where a reduction in the area of glaciers in excess of 36 percent since approximately 1850 has been reported (Key *et al.*, 2002). Munroe *et al.* used analyses of the sedimentary cores for properties sensitive to the extent and activity of upstream glacier ice, including water, organic matter, carbonate, and biogenic silica content; bulk density; mass accumulation rate; phosphorus fractionation; magnetic susceptibility; L*a*b* color values; and grain size distributions.

Munroe *et al.* report all but one of their records contain evidence for glacier advances during the last millennium, corresponding with the Little Ice Age, which they describe as “the most extensive event” of the entire Neoglacial and is “strongly expressed globally—Davis *et al.* (2009).” They found the Little

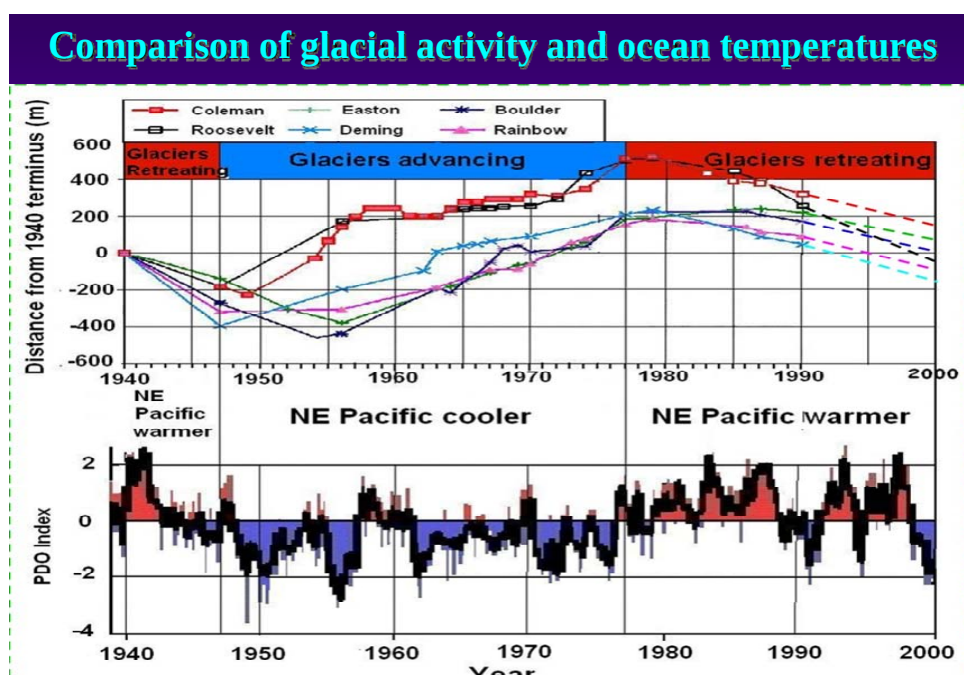


Figure 5.9.6.2. Comparison of advance and retreat of glaciers on Mt. Baker, Washington, with the Pacific Decadal Oscillation. Adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future*. Elsevier, pp. 3–51.

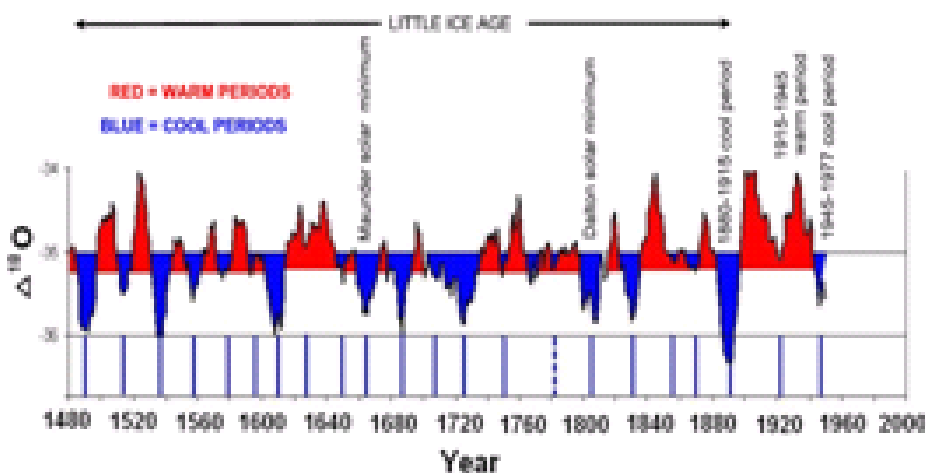


Figure 5.9.6.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460, based on data from Grootes and Stuiver, 1997). Also adapted from Easterbrook (2011).

Ice Age maximum advance was but the most recent in a series of advance/retreat cycles during the past several millennia, and its retreat “was the most dramatic episode of ice retreat in at least the last 1000 years.”

Some scientists argue, despite the fact human emissions did not reach significant levels until one-hundred years later, that the end of the Little Ice Age in the late nineteenth century was caused by CO_2 -

induced global warming. Munroe *et al.* are not among this group. Instead, they contend both the birth and the death of the Little Ice Age were promoted by changes in solar irradiance, a conclusion supported by many other authors (Denton and Karlen, 1973; Bond *et al.*, 2001; Koch *et al.*, 2007). The quasi-periodic cycle of ~1,500 years that is involved also has been connected to glacier fluctuations in Europe (Holzhauser *et al.*, 2005; Matthews *et al.*, 2005;

Nussbaumer *et al.*, 2011). If these scientists are right about solar influences, then atmospheric CO₂ variability (which remained constant during several 1,500-year cycles during the Holocene) is likely to have played no significant role in recent temperature changes.

Conclusions

The history of North American montane glaciers demonstrates the occurrence of repeated cool/warm cycles, well before any possible influence by human-emitted CO₂. In terms of the currently observed climatic pattern driven by the PDO, glaciers are behaving precisely as they have in the past; i.e. are starting a new, cooler 25- to 30-year cycle. Extending this record into the future provides an opportunity to predict coming climate changes.

These findings stand in stark contrast to the IPCC-endorsed “hockey stick” temperature history of Mann *et al.* (1998, 1999), which neither matches the known history of glacial change nor portrays any Northern Hemispheric warming until around 1910.

References

- Appenzeller, T. 2007. The big thaw. *National Geographic* (June): 56–71.
- Barclay, D.J., Wiles, G.C., and Calkin, P.E. 1999. A 1119-year tree-ring-width chronology from western Prince William Sound, southern Alaska. *The Holocene* **9**: 79–84.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Briffa, K.R. and Osborn, T.J. 2002. Blowing hot and cold. *Science* **295**: 2227–2228.
- Calkin, P.E., Wiles, G.C., and Barclay, D.J. 2001. Holocene coastal glaciation of Alaska. *Quaternary Science Reviews* **20**: 449–461.
- Carrara, P.E. and McGimsey, R.G. 1981. The late neoglacial histories of the Agassiz and Jackson Glaciers, Glacier National Park, Montana. *Arctic and Alpine Research* **13**: 183–196.
- Clague, J.J., Wohlfarth, B., Ayotte, J., Eriksson, M., Hutchinson, I., Mathewes, R.W., Walker, I.R., and Walker, L. 2004. Late Holocene environmental change at treeline in the northern Coast Mountains, British Columbia, Canada. *Quaternary Science Reviews* **23**: 2413–2431.
- Cook, E.R. 2002. Reconstructions of Pacific decadal variability from long tree-ring records. *EOS: Transactions*, *American Geophysical Union* **83**: S133.
- Davis, P.T., Menounos, B., and Osborn, G. 2009. Holocene and latest Pleistocene Alpine glacier fluctuations: a global perspective. *Quaternary Science Reviews* **28**: 1021–1033.
- Denton, G.H. and Karlen, W. 1973. Holocene climatic variations — their pattern and possible cause. *Quaternary Research* **3**: 155–205.
- Dowdeswell, J.A., Hagen, J.O., Björnsson, H., Glazovsky, A.F., Harrison, W.D., Holmlund, P., Jania, J., Koerner, R.M., Lefauconnier, B., Ommanney, C.S.L., and Thomas, R.H. 1997. The mass balance of circum-Arctic glaciers and recent climate change. *Quaternary Research* **48**: 1–14.
- Easterbrook, D.J. 2010. A walk through geologic time from Mt. Baker to Bellingham Bay. Chuckanut Editions.
- Easterbrook, D.J. 2011. Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future. Elsevier, pp. 3–51.
- Grootes, P.M. and Stuiver, M. 1997. Oxygen 18/16 variability in Greenland snow and ice with 10³ to 10⁵-year time resolution. *Journal of Geophysical Research* **102**: 26455e26470.
- Harper, J.T. 1993. Glacier terminus fluctuations on Mt. Baker, Washington, USA, 1940–1980, and climate variations. *Arctic and Alpine Research* **25**: 332–340.
- Holzhauser, H., Magny, M., and Zumbuhl, H.J. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* **15**: 789–801.
- Key, C.H., Fagre, D.B., and Menicke, R.R. 2002. Glacier retreat in Glacier National Park, Montana. In: Krimmel, R.M. (Ed.). *Glaciers of the Western United States*. U.S. Geological Survey, Reston, Virginia, USA, pp. J329–J381.
- Koch, J., Osborn, G.D., and Clague, J.J. 2007. Pre ‘Little Ice Age’ glacier fluctuations in Garibaldi Provincial Park, Coast Mountains, British Columbia, Canada. *The Holocene* **17**: 1069–1078.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* **392**: 779–787.
- Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.
- Matthews, J.A., Berrisford, M.S., Quentin Dresser, P., Nesje, A., Olaf Dahl, S., Elizabeth Bjune, A., Bakke, J., John, H., Birks, B., and Lie, O. 2005. Holocene glacier history of Bjornbreen and climatic reconstruction in central Jotunheimen, Norway, based on proximal glaciofluvial stream-bank mires. *Quaternary Science Reviews* **24**: 67–90.

Observations: The Cryosphere

Munroe, J.S., Crocker, T.A., Giesche, A.M., Rahlson, L.E., Duran, L.T., Bigl, M.F., and Laabs, B.J.C. 2012. A lacustrine-based Neoglacial record for Glacier National Park, Montana, USA. *Quaternary Science Reviews* 53: 39–54.

Nussbaumer, S.U., Steinhilber, F., Trachsel, M., Breitenmoser, P., Beer, J., Blass, A., Grosjean, M., Hafidner, A., Holzhauser, H., and Wanner H. 2011. Alpine climate during the Holocene: a comparison between records of glaciers, lake sediments and solar activity. *Journal of Quaternary Science* 26: 703–713.

Pederson, G.T., Fagre, D.B., Gray, S.T., and Graumlich, L.J. 2004. Decadal-scale climate drivers for glacial mass balance in Glacier National Park, Montana, USA. *Geophysical Research Letters* 31: L12203 10.1029/2004GL019770.

Wiles, G.C., D'Arrigo, R.D., Villalba, R., Calkin, P.E., and Barclay, D.J. 2004. Century-scale solar variability and Alaskan temperature change over the past millennium. *Geophysical Research Letters* 31: 10.1029/2004GL020050.

5.10 Sea and Lake Ice

Claims are commonly made that CO₂-induced global warming is melting sea ice in the Arctic, and potentially the Antarctic, and that such melting will accelerate as time passes.

Though semi-permanent sea ice exists today around the North Pole, fringing sea ice in both the Arctic and Antarctic is an annual, seasonal feature. Fringing sea ice is therefore particularly susceptible to fast advance or retreat depending upon local oceanographic and atmospheric changes. Quite major sea-ice changes are not uncommon and are not necessarily a result of climatic change; often, pulses of warm ocean water or atypical wind motions play a significant role.

Sea-ice expansion is driven by the spontaneous freezing of sea water in winter in areas of open polar ocean. Then, during the spring and summer months, and as daily solar radiation increases with higher Sun angle and longer day length, the sea ice melts and its area contracts. This annual cycle results in changes in area of sea ice of about 10 million km² each year in the Arctic and about 12 million km² in the Antarctic (see Figure 5.10.1).

The annual areal extent of sea ice is influenced by both ocean and atmospheric temperature, and in general the colder the winter the more sea ice that will form. The melting and break-up of sea ice is, however, more complex, in that winds and ocean currents often play a major role in breaking up, dispersing, and diminishing the area of sea ice, as was

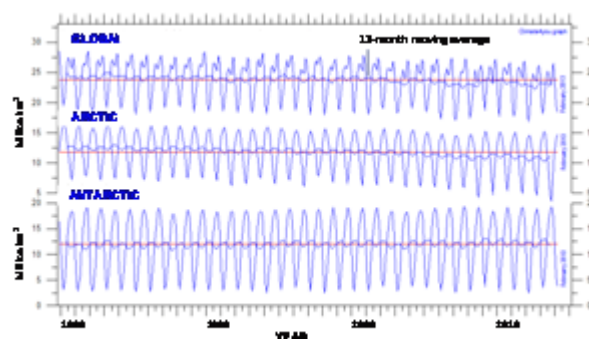


Figure 5.10.1. Arctic, Antarctic, and global sea ice area, 1979–2012 plotted using data from U.S. National Snow and Ice Data Center. Humlum, O. 2013. Sea ice extension in a longer time frame. Climate4You [Web site], <http://www.climate4you.com/SeaIce.htm>.

the case in the extensive diminution of ice in the Arctic Ocean in 2007 and 2012.

The freezing and melting of both land ice and sea ice is not just a simple function of temperature, but reflects complex changes in a number of environmental variables. The satellite observational record of sea ice spans only 1979–2012, and it has recently shown increases in ice area around Antarctica and decreases in area in the Arctic Ocean. There has been little net change in the overall global area of ice over the past 33 years, as shown in Figure 5.10.1. But 33 years is far too short a period of record from which to draw any meaningful conclusions about climate change.

Longer historical records demonstrate the area of Arctic ice has fluctuated in a multidecadal way in broad sympathy with past cycles in temperature, including shrinking to an area similar to that of recent years during periods of relative warmth in the 1780s and 1940s (see Figure 5.10.2) (Frauenfeld *et al.*, 2011). Earlier still, about 8,000 years ago during the early Holocene Climatic Optimum, geological records show temperatures up to 2.5° C warmer than today resulted in strong Arctic glacier melt and therefore probably an almost or completely ice-free Arctic Ocean (e.g., Fisher *et al.*, 2006).

References

- Fisher, D. *et al.*, 2006. Natural variability of Arctic sea ice over the Holocene. *EOS (Transactions of the American Geophysical Union)* 87: 273, 275, doi: 10.1029/2006EO280001.
- Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J.

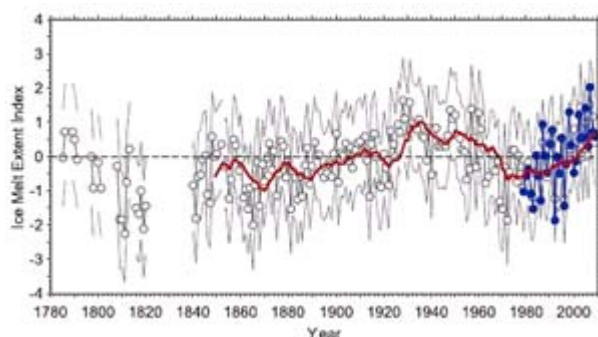


Figure 5.10.2. Estimated area of Arctic sea ice, 1780–2010. Adapted from Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784–2009. *Journal of Geophysical Research* **116**: doi:10.1029/2010JD014918.

2011. A reconstruction of annual Greenland ice melt extent, 1784–2009. *Journal of Geophysical Research* **116**: doi:10.1029/2010JD014918.

Humlum, O. 2013. Sea ice extension in a longer time frame. Climate4You [Web site], <http://www.climate4you.com/SeaIce.htm>.

5.10.1 Arctic Sea Ice

Arctic climate is complex and varies on a number of timescales with multiple causes (Venegas and Mysak, 2000). Identifying changes in Arctic sea ice that can be attributed to an increase in temperature caused by the burning of fossil fuels has proved difficult. The task is further complicated because most of the records used in the debate comprise only a few years to a few decades of data, and they yield different trends depending on the data set or period of time studied.

The dynamic, rather than climatic, aspect of sea-ice change is well exemplified in a recent satellite study by Scott and Marshall (2010), who aimed to resolve a dilemma: Whereas there has been a trend toward earlier summer breakup of sea ice in western Hudson Bay, Canada, which some authors (Stirling *et al.*, 1999; Gagnon and Gough, 2005) have attributed to long-term warming in the region, Dyck *et al.* (2007) report no regional warming trend has elapsed sufficient to have caused this change.

Scott and Marshall combined passive microwave data collected by the Nimbus 7 satellite and Defense Meteorological Satellite Program satellites with Canadian Ice Service sea-ice charts (cf. Agnew and Howell, 2002; Fetterer *et al.*, 2008) to assemble a new sea-ice time series for the period 1971–2007. The new record shows “there has clearly not been a continuous

trend in the [time of sea-ice breakup] data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date.” The authors observe an increase in regional southwesterly winds during the first three weeks of June, with a corresponding increase in surface temperature, were the likely causes of the earlier breakup.

A necessary longer-term context for considering changes in sea ice has been provided by the reconstruction by Vare *et al.* (2009) of spring sea-ice trends in the central Canadian Arctic Archipelago over the past 1,200 years. These authors applied the biomarker IP25, using a technique developed by Belt *et al.* (2007). IP25 is a mono-unsaturated highly branched isoprenoid synthesized by sea-ice diatoms that live in sediments on the seabed below sea ice, the abundance of which varies according to the degree of ice cover. Using a core from Barrow Strait (74°16.05'N, 91°06.38'W), Vare *et al.* measured a variety of proxy data that included IP25, other organic biomarkers, stable isotope composition of bulk organic matter, benthic foraminifera, particle size distributions, and ratios of inorganic elements.

Vare *et al.* documented a decrease in spring sea ice between approximately 1,200 and 800 years before present, followed by an increase in ice over the last 400 years of their record (between 800 and 400 years BP). That the area of sea ice was less during the Medieval Warm Period and more during the Little Ice Age is a result that could have been expected. Nonetheless, together with the demonstration by Frauenfeld *et al.* of the presence also of multidecadal cycles in sea-ice area, this result confirms many other studies that suggest Arctic sea ice is widely variable and the variability is a manifestation of known natural climatic rhythmicities.

References

- Agnew, T.A. and Howell, S. 2002. Comparison of digitized Canadian ice charts and passive microwave sea-ice concentrations. *Geoscience and Remote Sensing Symposium, IGARSS 2002* **1**: 231–233.
- Belt, S.T., Masse, G., Rowland, S.J., Poulin, M., Michel, C., and LeBlanc, B. 2007. A novel chemical fossil of palaeo sea ice: IP25. *Organic Geochemistry* **38**: 16–27.
- Dyck, M.G., Soon, W., Baydack, R.K., Legates, D.R., Baliunas, S., Ball, T.F., and Hancock, L.O. 2007. Polar bears of western Hudson Bay and climate change: are warming spring air temperatures the “ultimate” survival control factor? *Ecological Complexity* **4**: 73–84.

Observations: The Cryosphere

Fetterer, F., Knowles, K., Meier, W., and Savoie, M. 2008. *Sea ice index*. Boulder, Colorado: National Snow and Ice Data Center. http://nsidc.org/data/docs/noaa/g02135_seaice_index/index.html.

Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784–2009. *Journal of Geophysical Research* **116**: 10.1029/2010JD014918.

Gagnon, A.S. and Gough, W.A. 2006. East-west asymmetry in long-term trends of landfast ice thickness in the Hudson Bay region, Canada. *Climate Research* **32**: 177–186.

Scott, J.B.T. and Marshall, G.J. 2010. A step-change in the date of sea-ice breakup in western Hudson Bay. *Arctic* **63**: 155–164.

Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. *Arctic* **52**: 294–306.

Vare, L.L., Masse, G., Gregory, T.R., Smart, C.W., and Belt, S.T. 2009. Sea ice variations in the central Canadian Arctic Archipelago during the Holocene. *Quaternary Science Reviews* **28**: 1354–1366.

Venegas, S.A. and Mysak, L.A. 2000. Is there a dominant timescale of natural climate variability in the Arctic? *Journal of Climate* **13**: 3412–3434.

Earlier research

Clearly, the science pertaining to causes of Arctic sea-ice loss is not settled, as confirmed by the following other recent studies that address the issue.

- Rothrock *et al.* (1999) used submarine sonar measurements to establish that Arctic sea ice in the mid-1990s had thinned by about 42 percent of the average 1958–1977 thickness. The IPCC reported this result, but then commented more recent studies have found the reduction in ice thickness occurred abruptly before 1991, rather than being gradual, and acknowledged “ice thickness varies considerably from year to year at a given location and so the rather sparse temporal sampling provided by submarine data makes inferences regarding long term change difficult” (IPCC 2007, p. 353).
- Johannessen *et al.* (1999) analyzed Arctic sea ice extent over the period 1978–1998 and found it to have decreased by about 14 percent. The change occurred rather abruptly over a single period of not more than three years (1987/88–1990/91) and possibly only one year (1989/90–1990/91). This finding led them to suggest ice cover might be in a state of transition

which, if continued, “may lead to a markedly different ice regime in the Arctic,” as was also suggested by Vinnikov *et al.* (1999).

- Winsor (2001) analyzed a more comprehensive set of Arctic sea-ice data obtained from a transect of six submarine cruises conducted between 1991 and 1997. The transect data reveal mean Arctic sea-ice thickness had remained almost constant over the period of study. Data from the North Pole showed little variability, and a linear regression of the data revealed a “slight increasing trend for the whole period.” Combining these results with those from earlier studies, Winsor concludes “mean ice thickness has remained on a near-constant level around the North Pole from 1986 to 1997.”

- Parkinson (2000b) utilized satellite-derived data regarding sea-ice extent to calculate changes for the periods 1979–1990 and 1990–1999. In seven of the nine regions into which he divided the Arctic for his analysis, the “sign of the trend reversed from the 1979–1990 period to the 1990–1999 period,” indicative of the ease with which decadal trends are often reversed in this part of the world.

- Grumet *et al.* (2001) point out recent trends in Arctic sea-ice cover provide only “out of context” results, because their brevity does not allow for the consideration of interdecadal or multidecadal variability. Modern measurements of sea ice are simply available for too short a period for a climate trend to be demonstrated.

To overcome this problem, Grumet *et al.* developed a 1,000-year record of spring sea-ice conditions in Baffin Bay using sea-salt proxy records from an ice core from the Penny Ice Cap, Baffin Island. Their record demonstrates a period of reduced sea ice during the eleventh–fourteenth centuries, after which enhanced sea-ice conditions prevailed during the next 600 years. During the final (twentieth) century of the record period, “sea-ice conditions in the Baffin Bay/Labrador Sea region, at least during the last 50 years, are within ‘Little Ice Age’ variability.”

- Comiso *et al.* (2001) used 1979–1998 satellite imagery to analyze variability in the Odden ice tongue—a winter ice-cover blanket in the Greenland Sea with a length of about 1,300 km and an area up to 330,000 km². Surface air temperature data from nearby Jan Mayen Island provided the necessary meteorological record. Trend analyses revealed the ice tongue has exhibited no statistically significant change over the 20-year period considered. However, a proxy reconstruction of the Odden ice tongue for the

past 75 years suggested it was “a relatively smaller feature several decades ago,” due to the warmer temperatures that prevailed at that time.

- In another study of Arctic climate variability, Omstedt and Chen (2001) obtained a proxy record of the annual maximum extent of sea ice in the Baltic Sea over the period 1720–1997. They report a significant decline in sea ice around 1877, with greater variability in sea-ice extent in the preceding, colder, 1720–1877 period than in the ensuing, warmer, 1878–1997 period.

- Jevrejeva (2001) reconstructed an even longer record of Baltic sea-ice variability by summarizing historical data for the annual date of ice breakup at the northern port of Riga, Latvia, for 1529–1990. The historical time series was best described by a fifth-order polynomial, which identified four distinct periods of climatic transition: 1530–1640, warming with a tendency toward earlier ice breakup of nine days/century; 1640–1770, cooling with a tendency toward later ice breakup of five days/century; 1770–1920, warming with a tendency toward earlier ice breakup of 15 days/century; and 1920–1990, cooling with a tendency toward later ice breakup of 12 days/century.

- Vinje (2001) studied a wide area of Nordic seas (the Greenland, Iceland, Norwegian, Barents, and Western Kara Seas) and determined “the extent of ice in the Nordic Seas measured in April has decreased by 33% over the past 135 years.” Nearly half of this reduction occurred over the period 1860–1900, which spans a period during which atmospheric CO₂ concentration rose by only 7 ppm, and a later time (of sea-ice decline, as it happens) when CO₂ concentration rose by more than 70 ppm. Vinje’s study clearly suggests the increase in the air’s CO₂ content over the past 135 years has had nothing to do with changes in sea-ice cover.

- In a similar study of the Kara, Laptev, East Siberian, and Chukchi Seas, based on newly available long-term Russian observations, Polyakov *et al.* (2002) found fast-ice thickness trends in the different seas were “relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level,” and these smaller-than-expected trends in sea-ice cover “do not support the hypothesized polar amplification of global warming.”

- Similarly, in a study published the following year, Polyakov *et al.* (2003) report “over the entire Siberian marginal-ice zone the century-long trend is only -0.5% per decade,” while “in the Kara, Laptev, East

Siberian, and Chukchi Seas the ice extent trends are not large either: -1.1%, -0.4%, +0.3%, and -1.0% per decade, respectively.” Moreover, they say “these trends, except for the Chukchi Sea, are not statistically significant.”

- Holloway and Sou (2002), employing data-fed model runs, found “no linear trend [in Arctic sea ice volume] over 50 years is appropriate” over the last half of the twentieth century, noting their results indicated “increasing volume to the mid-1960s, decadal variability without significant trend from the mid-1960s to the mid-1980s, then a loss of volume from the mid-1980s to the mid-1990s.” They conclude “the volume [of sea ice] estimated in 2000 is close to the volume estimated in 1950.”

- Cavalieri *et al.* (2003) extended prior satellite-derived Arctic sea ice records several years back in time by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets. For the newly extended period of 1972–2002, they determined Arctic sea ice extent had declined at a mean rate of $0.30 \pm 0.03 \times 10^6$ km² per decade, and for the shortened period from 1979–2002 they found a mean rate of decline of $0.36 \pm 0.05 \times 10^6$ km² per decade; i.e., a rate 20 percent greater than the full-period rate. Serreze *et al.* (2002) also determined the downward trend in Arctic sea ice extent during the passive microwave era culminated with a record minimum value in 2002.

- Laxon *et al.* (2003) used an eight-year time series (1993–2001) of Arctic sea-ice thickness data derived from measurements of ice freeboard made by radar altimeters carried aboard ERS-1 and 2 satellites. The latitudes, between 65° and 81.5°N, covered the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. The measurements revealed “an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models,” undermining “the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent.” The researchers also showed “sea ice mass can change by up to 16% within one year,” all of which “contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming.”

Laxon *et al.* show errors are present in current simulations of Arctic sea ice and conclude, “until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and

Observations: The Cryosphere

future, changes in Arctic ice cover will be open to question.”

- Pfirman *et al.* (2004) analyzed Arctic sea-ice drift dynamics for 1979–1997 using monthly fields of ice motion obtained from the International Arctic Buoy Program. Their analysis indicated sea ice formed over shallow Arctic seas is transported across the central basin to be exported primarily through Fram Strait and, to lesser degrees, the Barents Sea and Canadian Archipelago. Within the central Arctic, the ice travel times for this journey averaged 4.0 years from 1984–85 through 1988–89, but only 3.0 years from 1990–91 through 1996–97. The enhanced rate of modern ice export to Fram Strait from the Beaufort Gyre reduced the amount of thick-ridged ice within the Arctic central basin of the Arctic and helped produce the sea-ice thinning observed in the 1980s and 1990s. Pfirman *et al.* comment the rapid change in ice dynamics between 1988 and 1990 was a “response to a weakening of the Beaufort high pressure system and a strengthening of the European Arctic low (a shift from lower North Atlantic Oscillation/Arctic Oscillation to higher NAO/OA index) [Walsh *et al.*, 1996; Proshutinsky and Johnson, 1997; Kwok, 2000; Zhang *et al.*, 2000; Rigor *et al.*, 2002].”

- Kwok (2004) used QuikSCAT backscatter, MY fractions from RADARSAT, and the record of ice export from satellite passive microwave observations to study Arctic sea-ice changes for 1999–2003. Their results show the coverage of Arctic MY sea ice at the beginning of each year of the study was 3,774 x 10³ km² in 2000, 3,896 x 10³ km² in 2001, 4,475 x 10³ km² in 2002, and 4,122 x 10³ km² in 2003, which represents an increase in sea-ice coverage of 9 percent overall.

- Belchansky *et al.* (2004) report the total Arctic January multiyear ice area declined at a mean rate of 1.4 percent per year for the period 1988–2001. In the autumn of 1996, however, they note, “a large multiyear ice recruitment of over 10⁶ km² fully replenished the previous 8-year decline in total area.” This replenishment was followed by an accelerated and compensatory decline during the subsequent four years. Though the period of study is too short to be conclusive, Kwok (2004) reports 75 percent of the interannual variation in January sea-ice area was explained by linear regression on two atmospheric parameters: the previous winter’s Arctic Oscillation index (a proxy for melt duration) and the previous year’s average sea level pressure gradient across the Fram Strait (a proxy for annual ice export).

- Heide-Jorgensen and Laidre (2004) examined

changes during 1979–2001 in the fraction of open water found within various pack-ice microhabitats of Foxe Basin, Hudson Bay, Hudson Strait, Baffin Bay-Davis Strait, northern Baffin Bay, and Lancaster Sound over a 23-year interval (1979–2001), using remotely sensed microwave measurements of sea-ice extent. Foxe Basin, Hudson Bay, and Hudson Strait showed small increasing trends in the fraction of open water, with the upward trends at all microhabitats studied ranging from 0.2% to 0.7% per decade. In contrast, in Baffin Bay-Davis Strait and northern Baffin Bay the open-water trend was downward, and at a mean rate for all open-water microhabitats studied of fully 1% per decade, and in Lancaster Sound the open-water trend was also downward, this time at a mean rate of 0.6% per decade.

In comparison with these open water changes, Heide-Jorgensen and Laidre report “increasing trends in sea ice coverage in Baffin Bay and Davis Strait (resulting in declining open-water) were as high as 7.5 percent per decade between 1979–1999 (Parkinson *et al.*, 1999; Deser *et al.*, 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002),” and comparable significant increases were detected back to 1953 along the West Greenland coast by Stern and Heide-Jorgensen (2003).

- Bamber *et al.* (2004) used high-accuracy ice-surface elevation measurements (from Krabill *et al.*, 2000) to evaluate 1996–2002 elevation changes in the largest icecap in the Eurasian Arctic—Austfonna, on the island of Nordaustlandet in northeastern Svalbard. The authors discovered the central and highest-altitude area of the icecap, 15 percent of its total area, “increased in elevation by an average of 50 cm per year between 1996 and 2002,” while “to the northeast of this region, thickening of about 10 cm per year was also observed.” The highest of these growth rates represents as much as a 40 percent increase in accumulation rate (Pinglot *et al.*, 2001).

Bamber *et al.* conclude the best explanation for the dramatic increase in icecap growth over the six-year study period is a large increase in precipitation associated with a concomitant reduction in sea-ice cover in this sector of the Arctic. They characterize the situational change by saying it simply represents the transfer of ice from the top of the sea (in this case, the Barents Sea) to the top of the adjacent land (the Austfonna icecap).

- Divine and Dick (2006) used historical April–August ice observations from Iceland, Greenland, Norwegian, and Barents Seas between 30°W to 70°E to construct time series of ice-edge positions for 1750–2002. The results showed the presence of

oscillations in ice cover with periods of about 60 to 80 years and 20 to 30 years, superimposed on a continuous negative trend corresponding to the “persistent ice retreat since the second half of the 19th century.” This retreat began well before anthropogenic CO₂ emissions could have had a measurable effect on Earth’s climate.

- Gagnon and Gough (2006) analyzed sea-ice variability in Hudson Bay, Canada (cf. Parkinson *et al.*, 1999) using data from 13 stations located along the shoreline of Hudson Bay (seven) and in surrounding nearby lakes (six). They compiled long-term weekly measurements of ice thickness and associated weather conditions for the period 1963–1993, discovering a statistically significant thickening of the ice cover over time occurred in western Hudson Bay, while a small, non-significant thinning occurred on the eastern side. These findings contradict the projections from general circulation models and also “the reduction in sea-ice extent and thickness observed in other regions of the Arctic.”

- Over the longer time scale, a study by Eldrett *et al.* (2007) provides further evidence that the IPCC’s view of melting sea ice is wrong. They used dynocyst fossils and palaeomagnetic dating to generate a new stratigraphy for three key northern Deep Sea Drilling Project/Ocean Drilling Program sites, finding evidence of “extensive ice-rafted debris, including macroscopic dropstones, in late Eocene to early Oligocene sediments from the Norwegian-Greenland Sea that were deposited between about 38 and 30 million years ago.” The data “indicate sediment rafting by glacial ice, rather than sea ice, and point to East Greenland as the likely source,” thus suggesting “the existence of [at least] isolated glaciers on Greenland about 20 million years earlier than previously documented.”

What is particularly interesting about these findings, as Eldrett *et al.* describe them, is they indicate the presence of glacial ice on Greenland at a time when ocean bottom-water temperatures were 5–8°C warmer and atmospheric CO₂ concentrations as much as four times greater than they are today.

Conclusions

The papers discussed above provide a litany of detailed findings as to the variability of Arctic sea-ice cover in association with natural changes in atmospheric, oceanographic, or ice dynamics. So far as specific changes are concerned—for example the widely reported thinning of Arctic sea ice during the 1990s—no evidence exists that such changes were forced by an increase in atmospheric CO₂ content.

Instead, the oscillatory behavior reported in so many ice studies implies the existence of “close connections between the sea ice cover and major oscillatory patterns in the atmosphere and oceans” (Parkinson, 2000b). This includes, *inter alia*, connections with the North Atlantic Oscillation (e.g., Hurrell and van Loon, 1997; Johannessen *et al.*, 1999; Kwok and Rothrock, 1999; Deser *et al.*, 2000; Kwok, 2000; Vinje, 2001); the spatially broader Arctic Oscillation (e.g., Deser *et al.*, 2000; Wang and Ikeda, 2000); the Arctic Ocean Oscillation (Polyakov *et al.*, 1999; Proshutinsky *et al.*, 1999); the “see-saw” in winter temperatures observed between Greenland and northern Europe (Rogers and van Loon, 1979); and an interdecadal Arctic climate cycle (Mysak *et al.*, 1990; Mysak and Power, 1992).

As concluded by Parkinson (2002), “The likelihood that Arctic sea ice trends are the product of such natural oscillations provides a strong rationale for considerable caution when extrapolating into the future the widely reported decreases in the Arctic ice cover over the past few decades or when attributing the decreases primarily to global warming.”

No substantial research study, including the papers discussed above, has demonstrated the level of sea ice in the Arctic Ocean stood at some “ideal” level prior to the Industrial Revolution. Instead, it is manifestly obvious that Arctic sea-ice cover varies dramatically and naturally over quite short periods of geological time. It is also clear Arctic fauna and flora, including the iconic polar bear, are well adapted to deal with the environmental exigencies that result. Regarding environmental policy formulation, it has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or human economic perspective.

References

- Bamber, J., Krabill, W., Raper, V., and Dowdeswell, J. 2004. Anomalous recent growth of part of a large Arctic ice cap: Austfonna, Svalbard. *Geophysical Research Letters* **31**: 10.1029/2004GL019667.
- Belchansky, G.I., Douglas, D.C., Alpatsky, I.V., and Platonov, N.G. 2004. Spatial and temporal multiyear sea ice distributions in the Arctic: A neural network analysis of SSM/I data, 1988–2001. *Journal of Geophysical Research* **109**: 10.1029/2004JC002388.
- Cavalieri, D.J., Parkinson, C.L., and Vinnikov, K.Y. 2003. 30-year satellite record reveals contrasting Arctic and Antarctic decadal sea ice variability. *Geophysical Research Letters* **30**: 10.1029/2003GL018031.

Observations: The Cryosphere

- Comiso, J.C., Wadhams, P., Pedersen, L.T., and Gersten, R.A. 2001. Seasonal and interannual variability of the Odden ice tongue and a study of environmental effects. *Journal of Geophysical Research* **106**: 9093–9116.
- Deser, C., Walsh, J., and Timlin, M.S. 2000. Arctic sea ice variability in the context of recent atmospheric circulation trends. *Journal of Climate* **13**: 617–633.
- Divine, D.V. and Dick, C. 2006. Historical variability of sea ice edge position in the Nordic Seas. *Journal of Geophysical Research* **111**: 10.1029/2004JC002851.
- Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., and Roberts, A.P. 2007. Continental ice in Greenland during the Eocene and Oligocene. *Nature* **446**: 176–179.
- Gagnon, A.S. and Gough, W.A. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. *Arctic* **58**: 370–382.
- Grumet, N.S., Wake, C.P., Mayewski, P.A., Zielinski, G.A., Whitlow, S.L., Koerner, R.M., Fisher, D.A., and Woollett, J.M. 2001. Variability of sea-ice extent in Baffin Bay over the last millennium. *Climatic Change* **49**: 129–145.
- Heide-Jorgensen, M.P. and Laidre, K.L. 2004. Declining extent of open-water refugia for top predators in Baffin Bay and adjacent waters. *Ambio* **33**: 487–494.
- Holloway, G. and Sou, T. 2002. Has Arctic sea ice rapidly thinned? *Journal of Climate* **15**: 1691–1701.
- Hurrell, J.W. and van Loon, H. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* **36**: 301–326.
- IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY.
- Jevrejeva, S. 2001. Severity of winter seasons in the northern Baltic Sea between 1529 and 1990: reconstruction and analysis. *Climate Research* **17**: 55–62.
- Johannessen, O.M., Shalina, E.V., and Miles, M.W. 1999. Satellite evidence for an Arctic sea ice cover in transformation. *Science* **286**: 1937–1939.
- Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J. 2000. Greenland ice sheet: High-elevation balance and peripheral thinning. *Science* **289**: 428–430.
- Kwok, R. 2000. Recent changes in Arctic Ocean sea ice motion associated with the North Atlantic Oscillation. *Geophysical Research Letters* **27**: 775–778.
- Kwok, R. 2004. Annual cycles of multiyear sea ice coverage of the Arctic Ocean: 1999–2003. *Journal of Geophysical Research* **109**: 10.1029/2003JC002238.
- Kwok, R. and Rothrock, D.A. 1999. Variability of Fram Strait ice flux and North Atlantic Oscillation. *Journal of Geophysical Research* **104**: 5177–5189.
- Laxon, S., Peacock, N., and Smith, D. 2003. High interannual variability of sea ice thickness in the Arctic region. *Nature* **425**: 947–950.
- Mysak, L.A., Manak, D.K., and Marsden, R.F. 1990. Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901–1984 and their relation to an interdecadal Arctic climate cycle. *Climate Dynamics* **5**: 111–133.
- Mysak, L.A. and Power, S.B. 1992. Sea-ice anomalies in the western Arctic and Greenland-Iceland Sea and their relation to an interdecadal climate cycle. *Climatological Bulletin/Bulletin Climatologique* **26**: 147–176.
- Omstedt, A. and Chen, D. 2001. Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. *Journal of Geophysical Research* **106**: 4493–4500.
- Parkinson, C.L. 2000a. Variability of Arctic sea ice: the view from space, and 18-year record. *Arctic* **53**: 341–358.
- Parkinson, C.L. 2000b. Recent trend reversals in Arctic sea ice extents: possible connections to the North Atlantic Oscillation. *Polar Geography* **24**: 1–12.
- Parkinson, C.L. 2002. Trends in the length of the Southern Ocean sea-ice season, 1979–99. *Annals of Glaciology* **34**: 435–440.
- Parkinson, C.L. and Cavalieri, D.J. 2002. A 21-year record of Arctic sea-ice extents and their regional, seasonal and monthly variability and trends. *Annals of Glaciology* **34**: 441–446.
- Parkinson, C.L., Cavalieri, D.J., Gloersen, P., Zwally, H.J., and Comiso, J.C. 1999. Arctic sea ice extents, areas, and trends, 1978–1996. *Journal of Geophysical Research* **104**: 20,837–20,856.
- Pfirman, S., Haxby, W.F., Colony, R., and Rigor, I. 2004. Variability in Arctic sea ice drift. *Geophysical Research Letters* **31**: 10.1029/2004GL020063.
- Pinglot, J.F., Hagen, J.O., Melvold, K., Eiken, T., and Vincent, C. 2001. A mean net accumulation pattern derived from radioactive layers and radar soundings on Austfonna, Nordaustlandet, Svalbard. *Journal of Glaciology* **47**: 555–566.
- Polyakov, I.V., Proshutinsky, A.Y., and Johnson, M.A. 1999. Seasonal cycles in two regimes of Arctic climate. *Journal of Geophysical Research* **104**: 25,761–25,788.
- Polyakov, I.V., Alekseev, G.V., Bekryaev, R.V., Bhatt, U.,

Colony, R.L., Johnson, M.A., Karklin, V.P., Makshtas, A.P., Walsh, D., and Yulin, A.V. 2002. Observationally based assessment of polar amplification of global warming. *Geophysical Research Letters* **29**: 10.1029/2001GL011111.

Polyakov, I.V., Alekseev, G.V., Bekryaev, R.V., Bhatt, U.S., Colony, R., Johnson, M.A., Karklin, V.P., Walsh, D., and Yulin, A.V. 2003. Long-term ice variability in Arctic marginal seas. *Journal of Climate* **16**: 2078–2085.

Proshutinsky, A.Y. and Johnson, M.A. 1997. Two circulation regimes of the wind driven Arctic Ocean. *Journal of Geophysical Research* **102**: 12,493–12,514.

Proshutinsky, A.Y., Polyakov, I.V., and Johnson, M.A. 1999. Climate states and variability of Arctic ice and water dynamics during 1946–1997. *Polar Research* **18**: 135–142.

Rigor, I.G., Wallace, J.M., and Colony, R.L. 2002. Response of sea ice to the Arctic oscillation. *Journal of Climate* **15**: 2648–2663.

Rogers, J.C. and van Loon, H. 1979. The seesaw in winter temperatures between Greenland and Northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. *Monthly Weather Review* **107**: 509–519.

Rothrock, D.A., Yu, Y., and Maykut, G.A. 1999. Thinning of the Arctic sea ice cover. *Geophysical Research Letters* **26**: 3469–3472.

Serreze, M.C., Maslanik, J.A., Scambos, T.A., Fetterer, F., Stroeve, J., Knowles, K., Fowler, C., Drobot, S., Barry, R.G., and Haran, T.M. 2003. A record minimum arctic sea ice extent and area in 2002. *Geophysical Research Letters* **30**: 10.1029/2002GL016406.

Stern, H.L. and Heide-Jorgensen, M.P. 2003. Trends and variability of sea ice in Baffin Bay and Davis Strait. *Polar Research* **22**: 11–18.

Vinje, T. 2001. Anomalies and trends of sea ice extent and atmospheric circulation in the Nordic Seas during the period 1864–1998. *Journal of Climate* **14**: 255–267.

Vinnikov, K.Y., Robock, A., Stouffer, R.J., Walsh, J.E., Parkinson, C.L., Cavalieri, D.J., Mitchell, J.F.B., Garrett, D., and Zakharov, V.R. 1999. Global warming and Northern Hemisphere sea ice extent. *Science* **286**: 1934–1937.

Walsh, J.E., Chapman, W.L., and Shy, T.L. 1996. Recent decrease of sea level pressure in the central Arctic. *Journal of Climate* **9**: 480–486.

Wang, J. and Ikeda, M. 2000. Arctic oscillation and Arctic sea-ice oscillation. *Geophysical Research Letters* **27**: 1287–1290.

Winsor, P. 2001. Arctic sea ice thickness remained constant during the 1990s. *Geophysical Research Letters* **28**: 1039–1041.

Zhang, J.L., Rothrock, D., and Steele, M. 2000. Recent changes in Arctic sea ice: The interplay between ice dynamics and thermodynamics. *Journal of Climate* **13**: 3099–3114.

5.10.2 Antarctic Sea Ice

Antarctic sea ice behavior continues to defy the expectations of those who believe that it should be shrinking rapidly under the influence of human-induced global warming (Figure 5.10.2.1). This is not a new finding, and other studies that have addressed this issue are listed below.

Landfast sea ice (fast ice) is sea ice held stationary by being attached to coastal features such as a rocky shoreline, glacier tongue, ice shelf, or grounded iceberg or shoal. Such fast ice is “a preeminent feature of the Antarctic coastal zone and an important interface between the ice sheet and pack ice/ocean” (Fraser *et al.*, 2012). Variability in fast ice extent is often viewed as a sensitive indicator of climate change (Murphy *et al.*, 1995; Heil *et al.*, 2006; Mahoney *et al.*, 2007).

Fraser *et al.* (2012) developed a high-resolution time series of landfast sea ice extent along the East Antarctic coast for the period March 2000–December 2008 using data from the MODIS (Resolution Imaging Spectroradiometer) satellite. The ice area study across East Antarctica (10°W to 172°E) revealed a statistically significant increase of $1.43 \pm 0.3\%$ per year, this trend agreeing with other short-term regional trends in overall sea ice (pack ice + fast ice) for different sectors of the coast (Cavalieri and Parkinson, 2008; Comiso, 2009).

Pezza *et al.* (2012) also report a modest increasing trend in sea-ice area around Antarctica over the era of satellite coverage, as documented by Watkins and Simmonds (2000), Zwally *et al.* (2002), Parkinson (2004), Turner *et al.* (2007), and Comiso and Nishio (2008). Pezza *et al.*’s broader study derived a history of Antarctic sea ice for 1979–2008, based upon remotely sensed data from the NASA’s Nimbus-7 SMMR and DMSP SSM/I passive microwave satellites. The results showed modest trends of increasing sea ice during all seasons, with the trends over spring and autumn being the most pronounced, involving an increase of about half-a-million square kilometers over the whole period. This equates with a 2–3 percent increase in sea-ice area during winter and spring and a 5–7 percent increase during summer. Pezza *et al.* report “the greatest [sea ice area] on record occurred during the 2007–2008 summer” when an increase in area of 8 percent occurred.

Observations: The Cryosphere

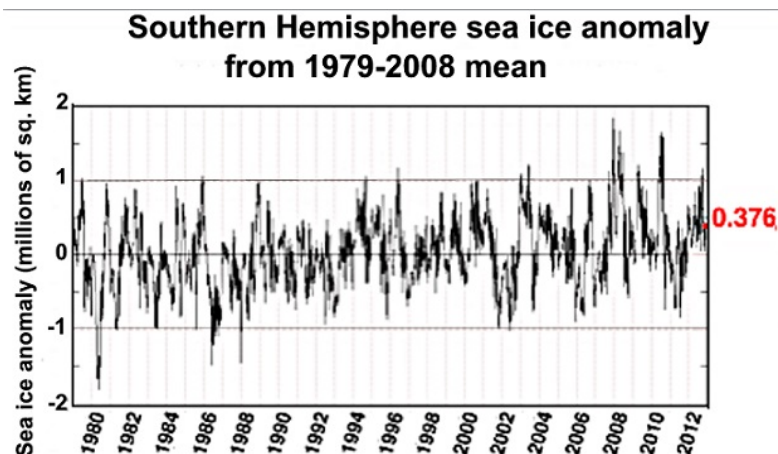
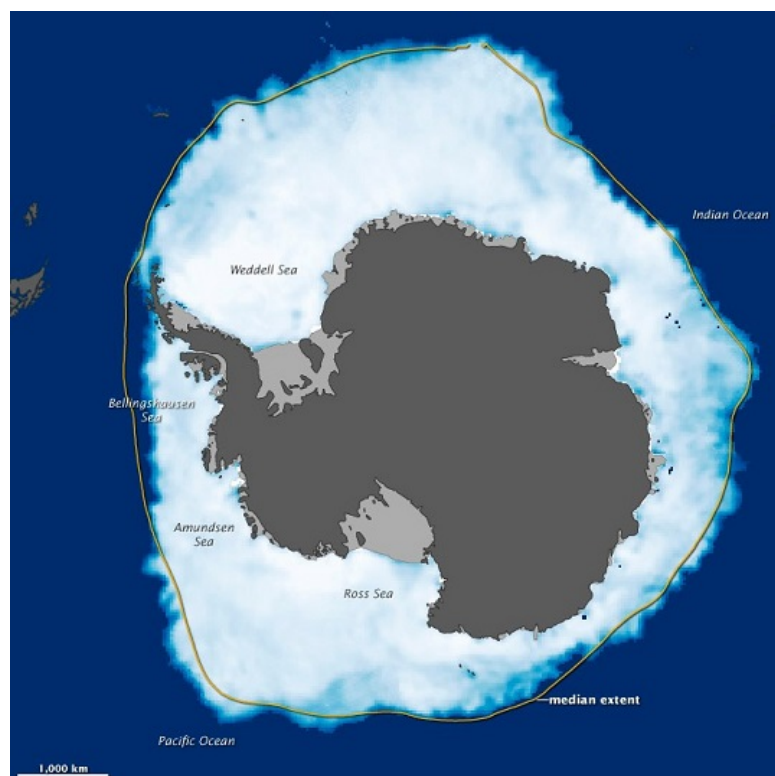


Figure 5.10.2.1. ABOVE Record sea ice area around Antarctica, attained in 2012 (NASA, 2012). BELOW Increase in Antarctic sea ice area since 1979 (graph from *Cryosphere Today*, University of Illinois).

References

Comiso, J. 2009. Variability and trends of the global sea ice cover. In: Thomas, D. and Dieckmann, G. (Eds.) *Sea Ice*, 2nd ed., Wiley-Blackwell, pp. 205–246.

Comiso, J.C. and Nishio, F. 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. *Journal of Geophysical Research* **113**: 10.1029/2007JC004257.

Cavalieri, D.J. and Parkinson, C.L. 2008. Antarctic sea ice variability and trends, 1979–2006. *Journal of Geophysical Research* **113**: 10.1029/2007JC004564.

Fraser, A.D., Massom, R.A., Michael, K.J., Galton-Fenzi, B.K., and Lieser, J.L. 2012. East Antarctic landfast sea ice distribution and variability, 2000–08. *Journal of Climate* **25**: 1137–1156.

Heil, P. 2006. Atmospheric conditions and fast ice at Davis, East Antarctica: A case study. *Journal of Geophysical Research* **111**: 10.1029/2005JC002904.

Mahoney, A., Eicken, H., Gaylord, A.G., and Shapiro, L. 2007. Alaska landfast sea ice: links with bathymetry and atmospheric circulation. *Journal of Geophysical Research* **112**: 10.1029/2006JC003559.

Murphy, E.J., Clarke, A., Symon, C., and Priddle, J.J. 1995. Temporal variation in Antarctic sea-ice: analysis of a long term fast-ice record from the South Orkney Islands. *Deep-Sea Research I* **42**: 1045–1062.

Parkinson, C.L. 2004. Southern Ocean sea ice and its wider linkages: insights revealed from models and observations. *Antarctic Science* **16**: 387–400.

Pezza, A.B., Rashid, H.A., and Simmonds, I. 2012. Climate links and recent extremes in Antarctic sea ice, high-latitude cyclones, Southern Annular Mode and ENSO. *Climate Dynamics* **38**: 57–73.

Turner, J., Overland, J.E., and Walsh, J.E. 2007. An Arctic and Antarctic perspective on recent climate change. *International Journal of Climatology* **27**: 277–293.

Watkins, A.B. and Simmonds, I. 2000. Current trends in Antarctic sea ice: the 1990s impact on a short climatology. *Journal of Climate* **13**: 4441–4451.

Zwally, H.J., Comiso, J.C., Parkinson, C.L., Cavalieri, D.J., and Gloersen, P. 2002. Variability of Antarctic sea ice 1979–1998. *Journal of Geophysical Research* **107**: 10.1029/2000JC000733.

Earlier Research

Antarctic sea ice behavior continues to defy the expectations of those who believe it should be shrinking rapidly under the influence of human-induced global warming. This is not a new finding;

other studies that have addressed this issue are summarized below.

- Watkins and Simmonds (2000) analyzed trends in sea ice that surrounds Antarctica using data for 1987–1996 collected by the Special Sensor Microwave Imager (SSM/I) on United States meteorological satellites. Statistically significant increases in the area and extent of sea ice³ were recorded over the period studied, and when the new data were combined with results for the preceding period of 1978–1987, sea ice continued to show increases over the summed period (1978–1996).

- Watkins and Simmonds' findings that Southern Ocean sea ice has increased in area, extent, and season length since at least 1978 are supported by other studies. Hanna (2001) provided an analysis of sea ice cover based on SSM/I data for 1987–1999 and found “an ongoing slight but significant hemispheric increase of $3.7 \pm 0.3\%$ in extent and $6.6 \pm 1.5\%$ in area.” Parkinson (2002) utilized satellite passive-microwave data to map the length of the sea-ice season throughout the Southern Ocean for each year of the period 1979–1999, finding a “much larger area of the Southern Ocean experienced an overall lengthening of the sea-ice season ... than experienced a shortening.” Updating the analysis two years later for the period 1978–2002, Parkinson (2004) reported a linear increase in 12-month running means of Southern Ocean sea ice extent of $12,380 \pm 1,730 \text{ km}^2$ per year.

- Elderfield and Rickaby (2000) conclude the sea-ice cover of the Southern Ocean during glacial periods may have been as much as double the coverage of modern winter ice. They suggest by restricting communication between the ocean and atmosphere, sea-ice expansion provides a mechanism for reduced CO₂ release by the Southern Ocean and thereby lower glacial atmospheric CO₂ during glaciations.

- Yuan and Martinson (2000) analyzed Special SSM/I data together with data derived from brightness temperatures measured by the Nimbus-7 Scanning Multichannel Microwave Radiometer, finding, among other things, the mean trend in the latitudinal location of the Antarctic sea-ice edge over the prior 18 years was an equatorward expansion of ice by 0.011° of latitude per year.

- Zwally *et al.* (2002) also utilized passive-microwave satellite data to study Antarctic sea ice trends. Over the 20-year period 1979–1998, they report the sea ice extent of the entire Southern Ocean increased by $11,181 \pm 4,190$ square km per year, or by $0.98 \pm 0.37\%$ per decade, while sea-ice area increased by nearly the same amount: $10,860 \pm 3,720$ square km per year, or by $1.26 \pm 0.43\%$ per decade. They observed the variability of monthly sea-ice extent declined from 4.0% over the first 10 years of the record to 2.7% over the last 10 years.

- Vyas *et al.* (2003) analyzed data from the multichannel scanning microwave radiometer carried aboard India's OCEANSAT-1 satellite for the period June 1999–May 2001, which they combined with data for the period 1978–1987 derived from passive microwave radiometers aboard earlier Nimbus-5, Nimbus-7, and DMSP satellites to study secular trends in sea-ice extent about Antarctica over the period 1978–2001. This work revealed a mean rate of increase in sea-ice extent for the entire Antarctic region of 0.043 million km² per year. Vyas *et al.* note also “the increasing trend in the sea ice extent over the Antarctic region may be slowly accelerating in time, particularly over the last decade,” commenting the “continually increasing sea ice extent over the Antarctic Southern Polar Ocean, along with the observed decreasing trends in Antarctic ice surface temperature (Comiso, 2000) over the last two decades, is paradoxical in the global warming scenario resulting from increasing greenhouse gases in the atmosphere.”

- In a similar study, Cavalieri *et al.* (2003) extended prior satellite-derived Antarctic sea ice records several years by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets with National Ice Center digital sea ice data. They found between 1977 and 2002 sea-ice extent around Antarctica increased at a mean rate of $0.10 \pm 0.05 \times 10^6 \text{ km}^2$ per decade.

- Similarly, Liu *et al.* (2004) used sea-ice concentration data from the scanning multichannel microwave radiometer on the Nimbus 7 satellite and the spatial sensor microwave/imager on several defense meteorological satellites to develop a quality-controlled history of Antarctic sea ice variability for 1979–2002. They found “overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (of $\sim 4,801 \text{ km}^2/\text{yr}$).” In addition, they determined the total Antarctic sea ice increased by $\sim 13,295 \text{ km}^2/\text{yr}$, at a greater than 95% confidence

³ The *area* of sea ice is defined as the summed area of ice not including enclosed gaps and leads; the *extent* of sea ice is always a greater number and is measured inclusive of gaps and leads.

Observations: The Cryosphere

level.

- Laine (2008) determined 1981–2000 trends of Antarctic sea-ice concentration and extent based on the Scanning Multichannel Microwave Radiometer (SSMR) and SSM/I for the spring-summer period of November/December/January. These analyses were carried out for the continent as a whole as well as for five longitudinal sectors emanating from the South Pole. Laine concludes “sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero.” Laine also reports “the Antarctic region as a whole and all the sectors separately show slightly positive spring-summer albedo trends.”
- Comiso and Nishio (2008) provide updated and improved estimates of trends in Arctic and Antarctic sea ice cover for the period 1978–2006 using data from the Advanced Microwave Scanning Radiometer (AMSR-E), the SSM/I, and the SMMR, where the data from the last two instruments were adjusted to be consistent with the AMSR-E data. Their findings indicate sea-ice extent and area in the Antarctic grew by $+0.9 \pm 0.2$ and $+1.7 \pm 0.35\%$ per decade, respectively.
- Cavalieri and Parkinson (2008) extend the analyses of sea ice time series reported by Zwally *et al.* (2002) from 20 years (1979–1998) to 28 years (1979–2006), based upon satellite-borne passive microwave radiometer data. The results indicate “the total Antarctic sea ice extent trend increased slightly, from $0.96 \pm 0.61\%$ per decade to $1.0 \pm 0.4\%$ per decade, from the 20- to 28-year period.” Corresponding numbers for Antarctic sea ice area trends were $1.2 \pm 0.7\%$ per decade and $1.2 \pm 0.5\%$ per decade. Over the last eight years of the study period, both the extent and area of Antarctic sea ice have continued to increase, with the former parameter increasing at a more rapid rate than it did over the 1979–1998 period.

Conclusions

Since they first became available in 1979, satellite-mounted sensors have provided evidence for the multidecadal growth of both pack ice and fast ice across the entire East Antarctic region, and this expansion continues today. These observations contradict the climate modeling that projects decreases in Antarctic sea ice.

References

Cavalieri, D.J. and Parkinson, C.L. 2008. Antarctic sea ice variability and trends, 1979–2006. *Journal of Geophysical Research* **113**: 10.1029/2007JC004564.

Cavalieri, D.J., Parkinson, C.L., and Vinnikov, K.Y. 2003. 30-year satellite record reveals contrasting Arctic and Antarctic decadal sea ice variability. *Geophysical Research Letters* **30**: 10.1029/2003GL018031.

Comiso, J.C. 2000. Variability and trends in Antarctic surface temperatures from in situ and satellite infrared measurements. *Journal of Climate* **13**: 1674–1696.

Comiso, J.C. and Nishio, F. 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. *Journal of Geophysical Research* **113**: 10.1029/2007JC004257.

Elderfield, H. and Rickaby, R.E.M. 2000. Oceanic Cd/P ratio and nutrient utilization in the glacial Southern Ocean. *Nature* **405**: 305–310.

Hanna, E. 2001. Anomalous peak in Antarctic sea-ice area, winter 1998, coincident with ENSO. *Geophysical Research Letters* **28**: 1595–1598.

Laine, V. 2008. Antarctic ice sheet and sea ice as regional albedo and temperature change, 1981–2000, from AVHRR Polar Pathfinder data. *Remote Sensing of Environment* **112**: 646–667.

Liu, J., Curry, J.A., and Martinson, D.G. 2004. Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters* **31**: 10.1029/2003GL018732.

National Aeronautics and Space Administration. 2012. Antarctic sea ice reaches new maximum extent. October 11, 2012. <http://earthobservatory.nasa.gov/IOTD/view.php?id=79369>.

Parkinson, C.L. 2002. Trends in the length of the Southern Ocean sea-ice season, 1979–99. *Annals of Glaciology* **34**: 435–440.

Parkinson, C.L. 2004. Southern Ocean sea ice and its wider linkages: insights revealed from models and observations. *Antarctic Science* **16**: 387–400.

Vyas, N.K., Dash, M.K., Bhandari, S.M., Khare, N., Mitra, A., and Pandey, P.C. 2003. On the secular trends in sea ice extent over the antarctic region based on OCEANSAT-1 MSMR observations. *International Journal of Remote Sensing* **24**: 2277–2287.

Watkins, A.B. and Simmonds, I. 2000. Current trends in Antarctic sea ice: The 1990s impact on a short climatology. *Journal of Climate* **13**: 4441–4451.

Yuan, X. and Martinson, D.G. 2000. Antarctic sea ice extent variability and its global connectivity. *Journal of Climate* **13**: 1697–1717.

Zwally, H.J., Comiso, J.C., Parkinson, C.L., Cavalieri, D.J., and Gloersen, P. 2002. Variability of Antarctic sea ice 1979–1998. *Journal of Geophysical Research* **107**: 10.1029/2000JC000733.

5.10.3 Lake Ice

Floating ice pack responsive to climatic fluctuations forms on large, intracontinental lakes as well as on the ocean, and Wang *et al.* (2010) provide an analysis of 70 years of such floating ice for the Great Lakes of North America. Their study covers the winters of 1972–73 to 2008–09 and comprises an analysis of time series of annual average ice area and basin winter average surface air temperature (SAT) and floating ice cover (FIC) for the Great Lakes, which they remind us “contain about 95% of the fresh surface water supply for the United States and 20% of the world.”

The primary data of interest are depicted in Figure 5.10.3.1, which shows after an initial four years of relative warmth and lower annual average ice area, SATs declined and FIC area rose. Then there began a long period of somewhat jagged SAT rise and FIC decline, both of which level out from about 1998 to 2006, after which SAT once again slowly declines and FIC slowly rises. Both parameters terminate at about the same value they exhibited initially.

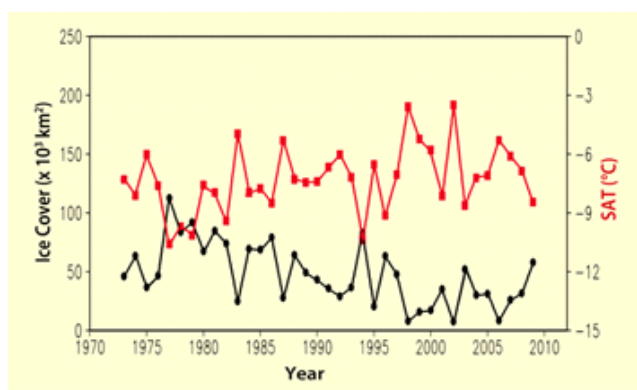


Figure 5.10.3.1. Annual average ice area of the North American Great Lakes and basin winter average surface air temperature (SAT) vs. time. Adapted from Wang, J., Bai, X., and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. *EOS, Transactions, American Geophysical Union* **91**: 41–42.

Conclusions

Wang *et al.* (2010) conclude “natural variability dominates Great Lakes ice cover” and the short-term trends present are “only useful for the period(s) studied.” There is therefore no reason to attribute any change in the annual average ice area of the North American Great Lakes to anthropogenic global warming. Similarly, Yoo and D’Odorico (2002) have shown northern high-latitude ice break-up follows a natural multidecadal rhythm rather than conforming to any long-term linear melting trend.

References

- Wang, J., Bai, X., and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. *EOS, Transactions, American Geophysical Union* **91**: 41–42.
- Winsor, P. 2001. Arctic sea ice thickness remained constant during the 1990s. *Geophysical Research Letters* **28**: 1039–1041.
- Yoo, J.C. and D’Odorico, P. 2002. Trends and fluctuations in the dates of ice break-up of lakes and rivers in Northern Europe: the effect of the North Atlantic Oscillation. *Journal of Hydrology* **268**: 100–112.

5.11 Late Pleistocene Glacial History

Geological studies have established that during the most recent major deglaciation since 20,000 years ago, multiple intense and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. This geological record of past climatic events provides an essential context missing from many current discussions of modern ice volume changes and their significance.

The results of oxygen isotope measurements from ice cores in the Greenland and Antarctic ice sheets several decades ago (see Section 5.7) stunned the scientific world (Dansgaard, 1987; Dansgaard and Oeschger, 1989; Dansgaard *et al.*, 1969, 1970, 1971, 1982, 1984, 1989; Jouzel *et al.*, 1987a, b, 1989; Oeschger *et al.*, 1983). Among the surprises was the delineation of multiple abrupt and intense periods of warming and cooling with a 1,500-year periodicity, which have come to be called Dansgaard-Oeschger (or D-O) events. The most precise records of these changes are the ice cores from the Greenland Ice Sheet Project (GISP) and the Greenland Ice Core Project (GRIP), which are especially important because the age of the ice at various levels in the cores has been established by counting annual layers, yielding a very accurate chronology of climatic fluctuations.

The Greenland GISP2 ice core shows temperatures for the past 100,000 years, of which the last 50,000 are presented in Figure 5.11.1 (upper). The later part of the last ice age (50,000–20,000 y BP) was followed by spasmodic and abrupt warming at the start of the Holocene at 11,700 y BP. More than a dozen episodes of abrupt warming and cooling occurred within the past 50,000 years, all of which accords well with other geologic evidence that had previously led to the recognition of several periods of warming and cooling. The named climatic periods, of which the cold Younger Dryas interval is the best

Observations: The Cryosphere

known (Figure 5.11.1, lower), were established from geological land studies long before their equivalents were recognized in deep sea mud cores and polar ice cores. In decreasing age, the major post-glacial climatic episodes delineated by geological studies comprise the Oldest Dryas (cold) Period, the Bølling (warm) Period, the Older Dryas (cold) Period, the Allerød (warm) Period, the Inter-Allerød (cold) Period, and the Younger Dryas (cold) Period.

The *Oldest Dryas Period* lasted between about 18,000 and 15,000 years BP (Roberts, 1998), with ^{14}C dates from the northwest shore of Lake Neuchâtel in Switzerland placing its termination at 14,650 y BP. Data derived from isotope variation of nitrogen and argon trapped in Greenland ice samples gives a second high-resolution date for the sharp temperature rise that ended it, 14,670 y BP. The significance of the Oldest Dryas is the abruptness of the warming that terminated it, during which temperatures in Greenland rose about 13°C in only a few centuries (Grootes and Stuiver, 1997; Cuffey and Clow, 1997).

The Greenland oxygen isotope record shows the *Bølling Warm Period* to lie between 14,600 and 14,100 BP. Abrupt, intense warming 14,500 years ago resulted in sudden wholesale melting of the huge continental ice sheets that covered North America, Europe, and Russia, and also an extensive retreat of alpine glaciers in discrete mountainous areas. This warming was remarkable because of both its abrupt onset and its intensity. Temperatures in Greenland rose $\sim 12^{\circ}\text{C}$ (which equals almost the total cooling of the late Pleistocene glaciation) to near present-day levels in about one century. As a result of the sudden, intense warming and melting, sea level rose sharply by perhaps as much as 18 m (Deschamps *et al.*, 2012). Although these temperature changes are cited for Greenland, simultaneous glacial retreats all over the world indicate the Bølling warming was global and characterized by temperatures at near-modern levels.

The Bølling was terminated by temperatures plummeting again from the thermal maximum by about 11°C in a few hundred years, thus initiating the *Older Dryas Period* from 14,300 to 14,000 BP. Temperatures returned to near full glacial level, and glaciers halted their rapid retreat.

About 14,000 years BP, temperatures rose abruptly again, and the *Allerød Warm Period* began and lasted until 12,800 years BP. Though the Allerød

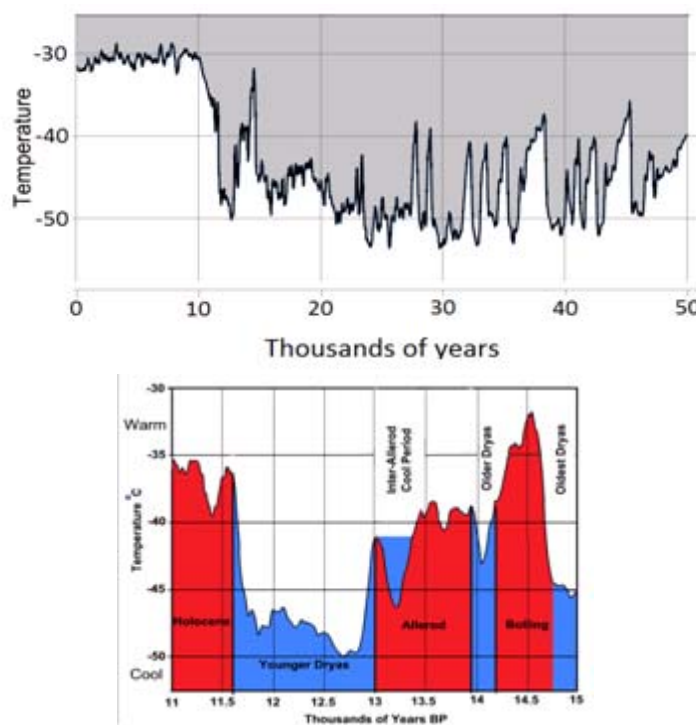


Figure 5.11.1. ABOVE. Greenland GISP2 air temperature curve for the past 50,000 years. Adapted from Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396. BELOW. Late glacial temperature fluctuations in the GISP2 Greenland ice core. Red = warm periods, blue = cold periods. Data from Cuffey and Clow (1997) and Alley, R.B. 2000, The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

was not as warm as today, or as during the Bølling, the rate of warming was still rapid, at $\sim 4.5^{\circ}\text{C}/\text{century}$. The interstadial ended abruptly with a cold period that reduced temperatures back to near-glacial levels within a decade.

Near the end of the Allerød warm period, temperatures dropped precipitously by $\sim 8^{\circ}\text{C}$ in about a century, to delineate what is called the *Inter-Allerød (cold) Period* (Grootes and Stuiver, 1997; Cuffey and Clow, 1997). Temperatures returned to nearly full Ice Age levels but persisted for only a few hundred years, so glaciers halted their retreat but did not rebuild to former extents. Then, just as suddenly as it had cooled, abrupt warming of $\sim 5^{\circ}\text{C}$ occurred, and temperatures returned to Allerød levels. In the Southern Hemisphere, the Allerød warming was interrupted by a colder period known as the *Antarctic Cold Reversal*, which lasted from $\sim 13,500$ –13,000 year BP (Grootes and Stuiver, 1997; Cuffey and Clow, 1997). This reversal is well documented in Antarctic

ice cores and also by glacial advances that occurred in New Zealand and are represented by the Birch Hill and Macaulay moraines in the Tekapo Valley of the Southern Alps (Easterbrook *et al.*, 2011).

The *Younger Dryas* is the longest and coldest of several very abrupt climatic changes near the end of the Pleistocene. It comprised a period of cold lasting about 1,300 years and ended as abruptly as it started. At the start of the event, 12,800 years ago, temperatures plunged $\sim 8^{\circ}\text{C}$ to full glacial levels. Glaciers, including remnants of the continental ice sheets, re-advanced, leaving moraines as footprints of their former presence. The end of the Younger Dryas occurred when temperatures rose sharply by $\sim 12^{\circ}\text{C}$ over about 50 years, to terminate the Pleistocene ice age about 11,500 years ago.

Radiocarbon and isotope dating of glacial moraines in regions all over the world, and abrupt steps in oxygen isotope ratios in the Greenland and Antarctic ice cores, indicate the Younger Dryas cooling was both globally widespread and synchronous. Evidence of Younger Dryas ice advance is reported from the Scandinavian ice sheet, the North American Laurentide and Cordilleran ice sheets, and the Russian ice sheet. Alpine and icecap glaciers also advanced during Younger Dryas cooling in both the Northern and Southern hemispheres, including many places in the Rocky Mountains of the United States and Canada, the Cascade Mountains of Washington in the United States, the European Alps, the Southern Alps of New Zealand, and the Patagonian Andes Mountains of South America.

The Younger Dryas cooling was not just a single climatic event. Not only did climatic warming and cooling occur both before and after it, but significant climate fluctuations also occurred within the Younger Dryas. That these were global events in both hemispheres is shown not only by correlations between ice cores from Greenland and Antarctica but also by the presence of dated, multiple glacial moraines around the world (Easterbrook *et al.*, 2011).

Figure 5.11.2 shows a plot of oxygen isotope variation within the Younger Dryas. Temperatures fluctuated up and down at least a dozen times, some brief warming periods reaching near-Allerød levels. Radiocarbon and cosmogenic dating of glacial moraines, and abrupt changes in oxygen isotope ratios in ice cores, indicate the Younger Dryas cooling was globally synchronous. That these climatic fluctuations were global in extent is shown by the occurrence of multiple Younger Dryas moraines around the world.

The type locality for the Younger Dryas is in Scandinavia, where the Scandinavian Ice Sheet

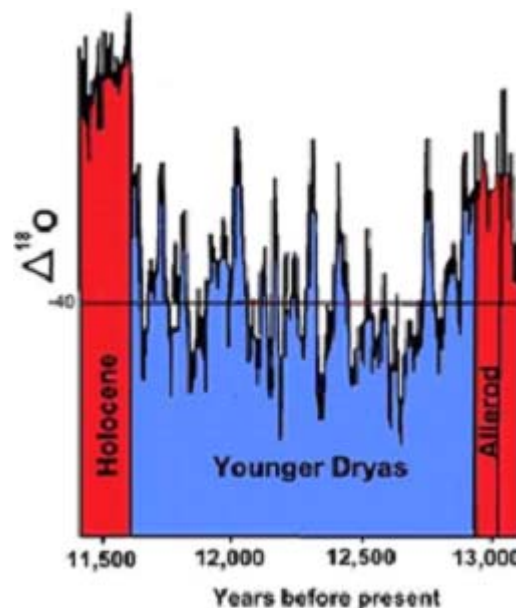


Figure 5.11.2. Oxygen isotope record from the Greenland ice core showing an abrupt temperature drop 12,800 years ago, 1,300 years of cool climate, and sudden warming 11,500 years ago (plotted from data in Grootes and Stuiver, 1997).

deposited two extensive Salpausselka end moraines across southern Finland, the central Swedish moraines, and the Ra moraines of southwestern Norway during the Younger Dryas. ^{14}C dates suggest an age of $\sim 10,700$ y BP for the outer Salpausselka moraine and $\sim 10,200$ y BP for the inner moraine, very similar to Younger Dryas moraines of the Cordilleran and Ice Sheets in North America. Thus, all three major Pleistocene ice sheets experienced multiple moraine-building episodes during the Younger Dryas.

Multiple Younger Dryas moraines also occur at Loch Lomond in the Scottish Highlands (e.g., Sissons, 1980; Ballantyne, 2002, 2006; Benn and Ballantyne, 2005; Bennett and Boulton, 1993; Rose *et al.*, 1998). Alpine glaciers and icefields in Britain readvanced or re-formed during the Younger Dryas and built extensive moraines at glacial margins. The largest Younger Dryas icefield at this time was the Scottish Highland glacier complex, but smaller alpine glaciers occurred in the Hebrides and Cairngorms of Scotland (Sissons, 1980), in the English Lake District, and in Ireland. The Loch Lomond moraines consist of one to several moraines, sometimes multiple, nested, recessional moraines. Radiocarbon dates constrain the age of the Loch Lomond moraines between 12.9 and 11.5 cal y BP.

Further south, in the Swiss Alps near St. Moritz, a complex moraine system contains two main moraine

Observations: The Cryosphere

ridges. The outer moraine has been dated by ^{10}Be , ^{26}Al , and ^{36}Cl at 11.75 ka and the inner moraine at 10.47 ka (Ivy-Ochs *et al.*, 1996, 1999; Kerschner *et al.*, 1999). At Maloja Pass, less than 10 km from Julier Pass, a bog just inside the outermost of three Egesen moraines was ^{14}C dated at 10,700 y B.P. (Heitz *et al.*, 1982).

post-LGM fluctuations of the CIS (Easterbrook, 1963, 1992, 2010; Easterbrook *et al.*, 2007; Kovanen and Easterbrook, 2002). The chronology of the ice margin fluctuations and timing of ice retreat during the Sumas Stade (Figure 5.11.3) are bracketed by 70 radiocarbon dates and tied to morphologic and stratigraphic evidence. The CIS chronology, which

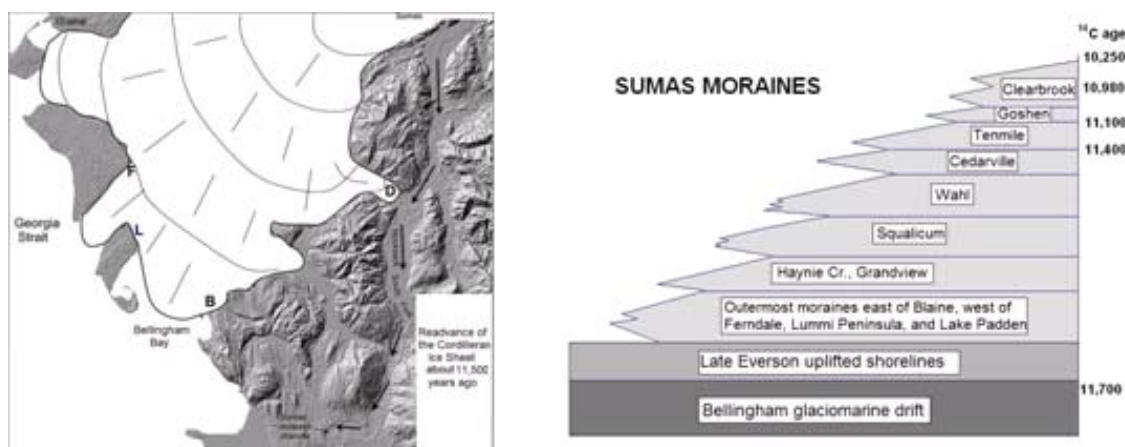


Figure 5.11.3. LEFT Reconstruction of the Cordilleran ice sheet at the end of the Pleistocene, 11,500 ^{14}C yrs. ago, NW Washington USA. RIGHT, Depiction of multiple Younger Dryas moraines from the Cordilleran ice sheet. From Easterbrook, D.J. 2012. Part 2 of Professor Don Easterbrook's concerns about the "Shakun *et al.* paper." Climate Observer [Web site] <http://climateobserver.blogspot.com/2012/04/part-2-of-professor-don-easterbrooks.html>.

Despite early evidence that a similar late-glacial readvance occurred in western North America (Armstrong, 1960; Easterbrook, 1963; Armstrong *et al.*, 1965), the apparent absence of the marker pollen evidence led some to believe the Younger Dryas did not occur in North America. Recent research has established the effects of the Younger Dryas as widespread at localities in the Pacific Northwest (Easterbrook, 1994a,b, 2002, 2003a,b; Easterbrook and Kovanen, 1998; Kovanen and Easterbrook, 2001, 2002), the Rocky Mountains (Licciardi *et al.*, 2004, Gosse *et al.*, 1995a,b; Easterbrook *et al.*, 2004), and California (Owen *et al.*, 2003). Planktonic microfossil records from the Pacific Northwest and Alaska also confirm the presence of a Younger Dryas event, with alkenone estimates of sea surface temperatures west of Vancouver Island indicating a temperature drop of 3°C (Kienast and McKay, 2001).

Morphologic, stratigraphic, and chronologic evidence of multiple moraines associated with oscillations of the remnants of the Cordilleran Ice Sheet (CIS) in the Fraser Lowland of British Columbia and Washington has revealed multiple

closely matches that of the GISP2 and GRIP ice cores from Greenland and sea surface temperatures in the north Pacific (Kienast and McKay, 2001), also compares well with the chronology of post-LGM alpine moraines in the western United States

Elsewhere in North America, Younger Dryas deposits are associated with an advance of the Laurentide Ice Sheet with dated moraine deposition in SW Canada (Grant and King, 1984; Stea and Mott, 1986, 1989); the expansion of cirque glaciers in the Wind River Range, Wyoming (Gosse *et al.*, 1995) and Sawtooth Range, Idaho (Easterbrook *et al.*, 2011); extensive moraine and ice-contact sediment deposition in the North Cascade Mountains (Kovanen and Easterbrook, 2001; Easterbrook *et al.*, 2010); cirque moraines in the Mt. Rainier part of the Cascade Range (Crandell and Miller, 1974); and multiple moraines near Icicle Creek (Page, 1939; Porter, 1976; Long, 1989; Easterbrook *et al.*, 2011).

In the Southern Hemisphere, multiple Younger Dryas moraines occur in the Southern Alps of New Zealand, for example at Arthur's Pass and at Birch Hills along Lake Pukaki. At the latter locality the

Younger Dryas moraines are located ~40 km up-valley from the last glacial maximum moraines. Younger Dryas moraines also occur at Prospect Hills in the Arrowsmith Range (Burrows, 1975) (Figure 5.11.4), and on the west coast of South Island, where wood in the Waihao Loop moraine, deposited by the Franz Josef Glacier about 20 km behind the LGM moraine, has been dated at 11,200 ^{14}C y BP (Mercer, 1982, 1988; Denton and Hendy, 1994).

Conclusions

Since the last glaciation, repeated rapid and often synchronous warmings and coolings have occurred across the globe, accompanied by concomitant glacial retreat and advance. The magnitude and intensity of these climatic fluctuations have been up to 20 times greater than modern warming during the past century.

The Younger Dryas is perhaps the most important of the climatic episodes, and the multiple nature of its moraines in both hemispheres indicates the occurrence of multiple climatic pulses (see Figure 5.11.5). The absence of a time lag between the Northern and Southern Hemisphere glacial fluctuations precludes an oceanic cause such as the North Atlantic Deep Ocean Water hypothesis for the cause of the Younger Dryas. Nor does a singular cosmic impact or volcanic origin seem likely because multiple Dansgaard/Oerscher warming and cooling events have recurred over periods of tens of thousands of years.

The most likely causation of the millennial rhythmicity that modulates major glacial-interglacial episodes is fluctuations in solar activity. What is certain is that none of the events were forced by changes in atmospheric carbon dioxide.

References

- Alley, R.B. 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.
- Armstrong, J.A. 1960. Surficial geology of the Sumas map area, British Columbia. *Geological Survey of Canada Paper* 92 G/1: p. 27.
- Armstrong, J.A., Crandell, D.R., Easterbrook, D.J., and Noble, J. 1965. Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington. *Geological Society of America Bulletin* **76**: 321–330.
- Ballantyne, C.K. 2002. The Loch Lomond Readvance on the Isle of Mull, Scotland: glacier reconstruction and palaeoclimatic implications. *Journal of Quaternary Science* **17**: 759–771. doi: 10.1002/jqs.729.

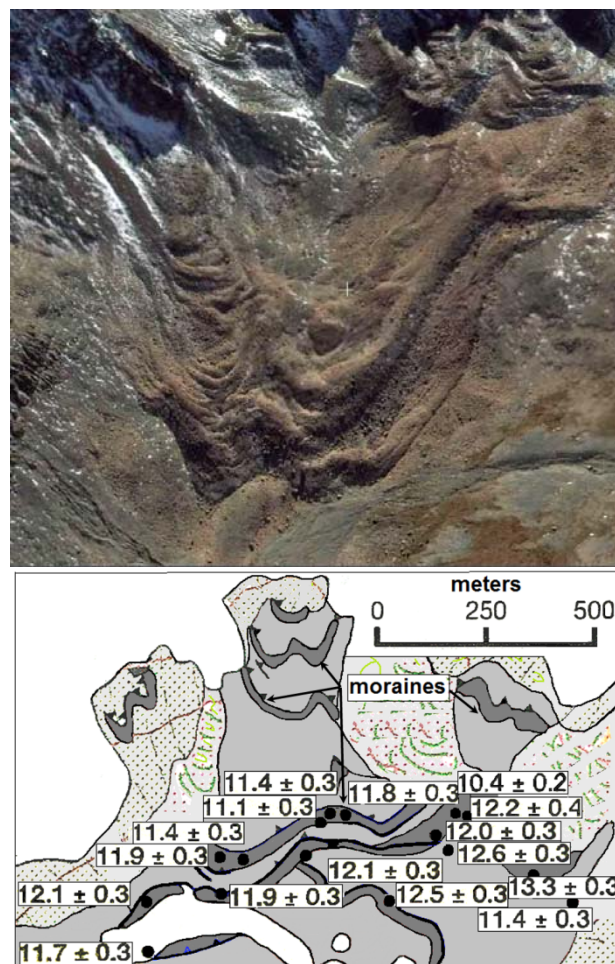


Figure 5.11.4. Moraines of the Younger Dryas ice advance in Irishman Basin, New Zealand Southern Alps. TOP: Aerial photograph. BOTTOM: Cosmogenic dates in thousands of years. Adapted from Kaplan, M.R., Schaefer, J.M., Denton, G.H., Barrell, D.A., Chinn, T.J.H., Putnam, A.E., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A.M. 2010. Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* **3**: 194–197.

- Ballantyne, C.K. 2006. Loch Lomond stadial glaciers in the Uig Hills, Western Lewis, Scotland. *Scottish Geographical Journal* **122**: 256–273. doi:10.1080/14702540701235001.
- Benn, D.I. and Ballantyne, C.K. 2005. Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland. *Journal of Quaternary Science* **20**: 577–592.
- Bennett, M.R. and Boulton, G.S. 1993. Deglaciation of the Younger Dryas or Loch Lomond Stadial ice-field in the Northern Highlands, Scotland. *Journal of Quaternary Science* **8**: 133–145.
- Burrows, C.J. 1975. Late Pleistocene and Holocene moraines of the Cameron Valley, Arrowsmith Range, Canterbury, New Zealand. *Arctic and Alpine Research* **7**: 125–140.

Observations: The Cryosphere

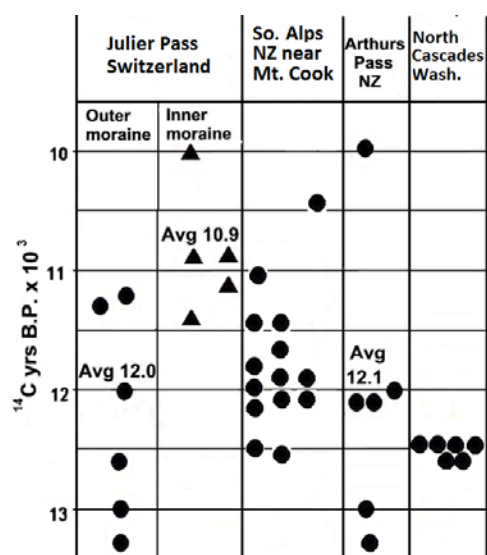


Figure 5.11.5. Ages of Younger Dryas moraines in New Zealand and the Swiss Alps. Adapted from Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149; and Easterbrook, D.J., Gosse, J., Sherrard, C., Steverson, E.B., and Finkel, R. 2011. Evidence for synchronous global climatic events: cosmogenic exposure ages of glaciations. In: *Evidence-Based Climate Science*, Easterbrook, D.J. (Ed.), pp. 53–88.

Crandell, D.R. and Miller, R.D. 1974. Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington. U.S. Geological Survey Professional Paper 450-D: 59.

Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396.

Dansgaard, W. 1987. Ice core evidence of abrupt climatic changes. In: Berger, W.J. and Labeyrie, L.D. (Eds.) *Abrupt climatic change: Evidence and implications*. Reidel, Dordrecht, Netherlands, pp. 223–233.

Dansgaard, W. and Oeschger, H. 1989. Past environmental long-term records from the Arctic. In: Oeschger, H. and Langway, C.C. (Eds.) *The Environmental Record in Glaciers and Ice Sheets*. John Wiley and Sons, NY, v. 8, pp. 287–317.

Dansgaard, W., Johnsen, S.J., Moeller, J., and Langway, C.C. 1969. One thousand centuries of climatic record from Camp Century on the Greenland Ice Sheet: *Science* **166**: 377–381.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., and Langway,

C.C., Jr. 1970. Ice cores and paleoclimatology. In Olsson, U., ed., *Twelfth Nobel Symposium, Radiocarbon variations and absolute chronology*. John Wiley and Sons, NY, pp. 337–351.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., and Langway, C.C. 1971. Climatic record revealed by the Camp Century ice core. In Turekian, K.K., ed., *Late Cenozoic glacial ages*. Yale University Press, New Haven, Connecticut, pp. 37–56.

Dansgaard, W., Clausen, H.B., Gundestrup, N., Hammer, C.U., Johnsen, S.J., Kristinsdottir, P.M., and Reeh, N. 1982. A new Greenland deep ice core. *Science* **218**: 1273–1277.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N., Hammer, C.U., and Oeschger, H. 1984. North Atlantic climatic oscillations revealed by deep Greenland ice cores. In Hansen, J.E. and Takahashi, T. (Eds.) *Climate Processes and Climate Sensitivity*. Geophysical Monograph **29** (Maurice Ewing) **5**: 288–298.

Dansgaard, W., White, J.W.C., and Johnsen, S.J. 1989. The abrupt termination of the Younger Dryas climate event. *Nature* **339**: 532–533.

Denton, G.H. and Hendy, C.H. 1994. Younger Dryas age advance of Franz Josef Glacier in the Southern Alps of New Zealand. *Science* **264**: 1434–1437.

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J., and Yokoyama, Y. 2012. Ice-sheet collapse and sea-level rise at the Bølling warming 14,600 years ago. *Nature* **483**: 559–564. doi:10.1038/nature10902.

Easterbrook, D.J. 1963. Late Pleistocene glacial events and relative sea-level changes in the northern Puget Lowland, Washington. *Geological Society of America Bulletin* **74**: 1465–1483.

Easterbrook, D.J. 1992. Advance and retreat of Cordilleran Ice Sheets in Washington, USA. *Geographie physique et Quaternaire* **46**: 51–68.

Easterbrook, D.J. 1994. Stratigraphy and chronology of early to late Pleistocene glacial and interglacial sediments in the Puget Lowland, Washington. In: Swanson, D.A. and Haugerud, R.A. (Eds.) *Geologic Field Trips in the Pacific Northwest*. Geological Society of America, pp. 1J23–1J38.

Easterbrook, D.J. 2003. Synchronicity and sensitivity of alpine and continental glaciers to abrupt, global, climate changes during the Younger Dryas. *Geological Society of America, Abstracts with Program* **35**: 35.

Easterbrook, D.J., 2010. A walk through geologic time from Mt. Baker to Bellingham Bay. Chuckanut Editions.

From Easterbrook, D.J. 2012. Part 2 of Professor Don Easterbrook's concerns about the "Shakun et al paper."

Climate Change Reconsidered II

Climate Observer [Web site] <http://climateobserver.blogspot.com/2012/04/part-2-of-professor-don-easterbrooks.html>.

Easterbrook, D.J. and Kovanen, D.J. 1998. Pre-Younger Dryas resurgence of the southwestern margin of the Cordilleran Ice Sheet, British Columbia, Canada: Comments. *Boreas* **27**: 229–230.

Easterbrook, D.J., Kovanen, D.J., and Slaymaker, O. 2007. New developments in Late Pleistocene and Holocene glaciation and volcanism in the Fraser Lowland and North Cascades, Washington. In: Stelling, P. and Tucker, D.S. (Eds.) *Geological Society of America Field Guide* **9**: 36–51.

Easterbrook, D.J., Gosse, J., Sherrard, C., Stevemspm, E.B., and Finkel, R. 2011. Evidence for synchronous global climatic events: cosmogenic exposure ages of glaciations. In: *Evidence-Based Climate Science*, Easterbrook, D.J. (Ed.), pp. 53–88.

Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., and Middleton, R. 1995. Precise cosmogenic ^{10}Be measurements in western North America: support for a global Younger Dryas cooling event. *Geology* **23**: 877–880.

Grant, D.R. and King, L.H. 1984. *A Stratigraphic Framework for the Quaternary History of the Atlantic Provinces, Canada*, Geological Survey of Canada **84-10**:173–191.

Grootes, P.M. and Stuiver, M. 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^3 to 10^5 -year time resolution. *Journal of Geophysical Research* **102**: 26,455–26,470.

Heitz A, Punchakunnel P., and Zoller H. 1982. Zum Problem der ^{14}C -Datierung im Veltlin und Oberengadin. *Physische Geographie* **1**: 91–101.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149.

Jouzel, J., Lorius, C., Petit, J.R., Genthon, C., Barkov, N.I., Kotlyakov, V.M., and Petrov, V.M. 1987. Vostock ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature* **329**: 403–408.

Jouzel, J., Lorius, C., Merlivat, L., and Petit, J.R. 1987. Abrupt climatic changes: the Antarctic ice record during the late Pleistocene. In Berger, W.H. and Labeyrie, L.D. (Eds.) *Abrupt Climatic Change: Evidence and Implications*. Reidel Publishing Company, Dordrecht, Netherlands, pp. 235–245.

Jouzel, J. et al. 1989. A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. *Quaternary Research* **31**: 135–150.

Kaplan, M.R., Schaefer, J.M., Denton, G.H., Barrell, D.A., Chinn, T.J.H., Putnam, A.E., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A.M. 2010. Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* **3**: 194–197.

Kerschner, H., Ivy-Ochs, S., and Schluchter, C. 1999. Palaeoclimatic interpretation of the early late-glacial glacier in the Gschnitz valley, central Alps, Austria. *Annals of Glaciology* **28**: 135–140.

Kienast, S.S. and McKay, J.L. 2001. Sea surface temperatures in the subarctic Northeast Pacific reflect millennial-scale climate oscillations during the last 16 kyrs. *Geophysical Research Letters* **28**: 1563–1566.

Kovanen, D.J. and Easterbrook, D.J. 2001. Late Pleistocene, post-Vashon, alpine glaciation of the Nooksack drainage, North Cascades, Washington. *Geological Society of America Bulletin* **113**: 274–288.

Kovanen, D.J. and Easterbrook, D.J. 2002. Extent and timing of Allerød and Younger Dryas age (ca. 12,500–10,000 ^{14}C yr BP) oscillations of the Cordilleran Ice Sheet in the Fraser Lowland, Western North America. *Quaternary Research* **57**: 208–224.

Licciardi, J.M., Clark, P.U., Brook, E.J., Elmore, D., and Sharma, P. 2004. Variable responses of western U.S. glaciers during the last deglaciation. *Geology* **32**: 81–84.

Long, W.A. 1989. A probable sixth Leavenworth glacial substage in the Icicle-Chiwaukum Creeks area, North Cascades Range, Washington. *Northwest Science* **63**: 96–103.

Mercer, J.H. 1982. Simultaneous climatic change in both hemispheres and similar bipolar inter-glacial warming: evidence and implications. *Geophysical Monograph* **29**: 307–313.

Mercer, J.H. 1988. The age of the Waiho Loop terminal moraine, Franz Josef Glacier, Westland, New Zealand. *New Zealand Journal of Geology and Geophysics* **31**: 95–99.

Oeschger, H., Beer, J., Siegenthaler, U., Stauffer, B., Dansgaard, W., and Langway, C.C., Jr. 1983. Late glacial climate history from ice cores. In Hansen, J.E. and Takahashi, T. (Eds.) *Climate Processes and Climate Sensitivity*. Geophysical Monograph **29** (Maurice Ewing) 5: 299–306.

Owen, L.A., Finkel, R.C., Minnich, R.A., and Perez, A.E. 2003. Extreme southwestern margin of late Quaternary glaciation in North America: timing and controls. *Geology* **31**: 729–732.

Page, B.M. 1939. Multiple alpine glaciation in the Leavenworth area, Washington. *Journal of Geology* **47**: 785–815.

Observations: The Cryosphere

Porter, S.C. 1976. Pleistocene glaciation in the southern part of the North Cascade Range, Washington. *Geological Society of America Bulletin* **87**: 61–75.

Roberts, N. 1998 (2nd ed.). *The Holocene: An Environmental History*. Blackwell, Oxford University Press.

Rose, J., Lowe, J.J., and Switsur, R. 1998. A radiocarbon date on plant detritus beneath till from the type area of the Loch Lomond readvance, Scotland. *Journal of Geology* **24**: 113–124.

Sissons, J.B. 1980. The Loch Lomond advance in the Lake District, northern England. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **71**: 12–27.

Stea, R.R. and Mott, R.J. 1986. Late-glacial climatic oscillation in Atlantic Canada equivalent to the Allerod/Younger Dryas event. *Nature* **323**: 247–250.

Stea, R.R. and Mott, R.J. 1989. Deglaciation environments and evidence for glaciers of Younger Dryas age in Nova Scotia, Canada. *Boreas* **18**: 169–187.

5.12 Holocene Glacial History

The climatic changes seen during the late Pleistocene continued, albeit at a lesser amplitude than for Dansgaard-Oeschger events, during the last 11,700 years (Holocene Period). Holocene climatic variability is well encapsulated by the temperature curve inferred from oxygen isotope measurements in Greenland ice cores (see Figure 5.12.1).

The five most important characteristics of the documented variability are the presence of a temperature peak about 2° C warmer than today during the Holocene climatic optimum, ~8,000 y BP; the general cooling trend that occurred thereafter; the punctuation of the record by 1,500-year-long alternating rhythms of warmer and colder climate (the Bond Cycle, of probable solar origin: Bond *et al.*, 1997; Wanner *et al.*, 2008); that for the great majority of the last 10,000 years temperature has been warmer than today; and that none of the climatic fluctuation during the Holocene was accompanied by parallel fluctuations in carbon dioxide.

A conspicuous larger climatic event occurred 8,200 years ago, when the Holocene record was interrupted by a sudden global cooling that lasted for 200 years (Figure 5.12.2). During this time, alpine glaciers advanced and built moraines (Easterbrook, 2011). Neither the abrupt climatic cooling nor the abrupt warming that followed was accompanied by atmospheric CO₂ changes.

Most of the climatic episodes indicated by the Greenland climate record also were recorded by historic sources. Egyptian records from before the founding of the Roman Empire show a cool climatic period from about 750 to 450 BC, with the Tiber River freezing and snow remaining on the ground for long periods (Singer and Avery, 2007). The Roman Warm Period (200–600 AD) followed, when the Romans wrote of grapes and olives growing farther north in Italy than had been previously possible.

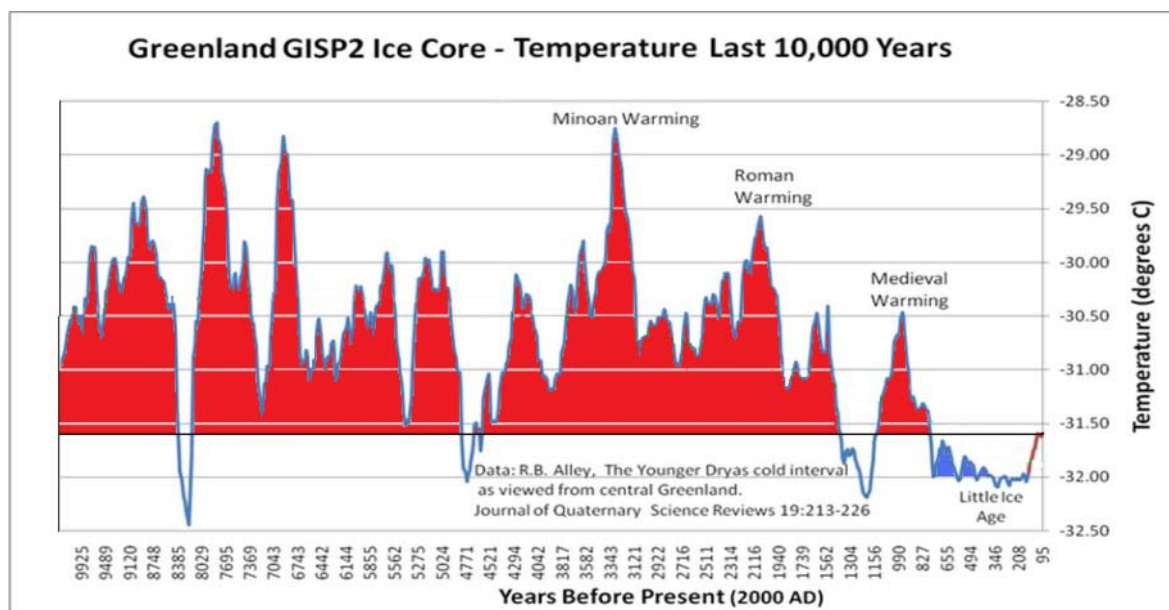


Figure 5.12.1. Temperature over the last 10,000 y from the GISP2 ice core, Greenland. Adapted from Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

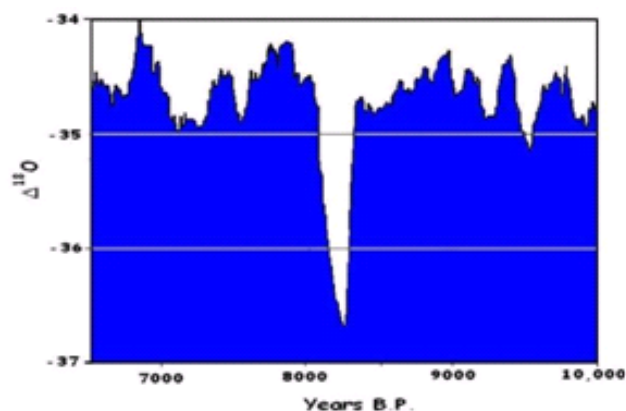


Figure 5.12.2. The 8,200 y BP sudden cooling recorded in oxygen isotope ratios in the GISP2 ice core. Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

The ensuing Dark Ages Cool Period (440–900 AD) was characterized by marked cooling again, with 540 AD marking a particularly cold year when tree rings were retarded, fruit didn't ripen, and snow fell in summer in Southern Europe. In addition, in 800 AD the Black Sea froze, and in 829 AD the Nile River froze (Oliver, 1973).

The Medieval Warm Period (900–1300 AD) that followed was marked by global temperatures warmer than at present, as indicated by the flourishing of grain crops, elevation of alpine tree lines, and building of many new towns and cities as the European population more than doubled. The Vikings took advantage of the climatic amelioration to

colonize Greenland in 985 AD, when milder climates allowed favorable open-ocean conditions for navigation and fishing. Wine grapes were grown about 500 km north of present vineyards in France and Germany, and also in the north of England (Oliver, 1973; Tkachuck, 1983). Wheat and oats were grown around Trondheim, Norway, suggesting climates about one degree C warmer than the present (Fagan, 2009).

After the Medieval Warm Period, temperatures in Europe dropped by as much as ~4° CC in ~20 years as the Little Ice Age (1300-1860 AD) commenced.

Though the overall cold lasted for 400 years, climate rhythmicity was maintained throughout, as manifest by 25 cold-warm oscillations (see Figure 5.12.3). During cold phases, the bitter winters and cool, rainy summers were too cool for satisfactory growth of cereal crops, which resulted in devastating crop failure, famine, and disease. Three years of torrential rains that began in 1315 led to the Great Famine of 1315–1317, and during colder winters the Thames River in London and canals in the Netherlands froze over (Grove, 1988, 2004; Fagan, 2001). Glaciers expanded worldwide during the Little Ice Age (Grove, 2004; Singer and Avery, 2007), with Greenland pack-ice extending well south in the North Atlantic in the thirteenth century (Singer and Avery, 2007). Glacial advances in the Swiss Alps in the mid-seventeenth century gradually encroached on farms and buried entire villages.

Elsewhere in the world, New York Harbor froze in the winter of 1780; sea ice surrounding Iceland

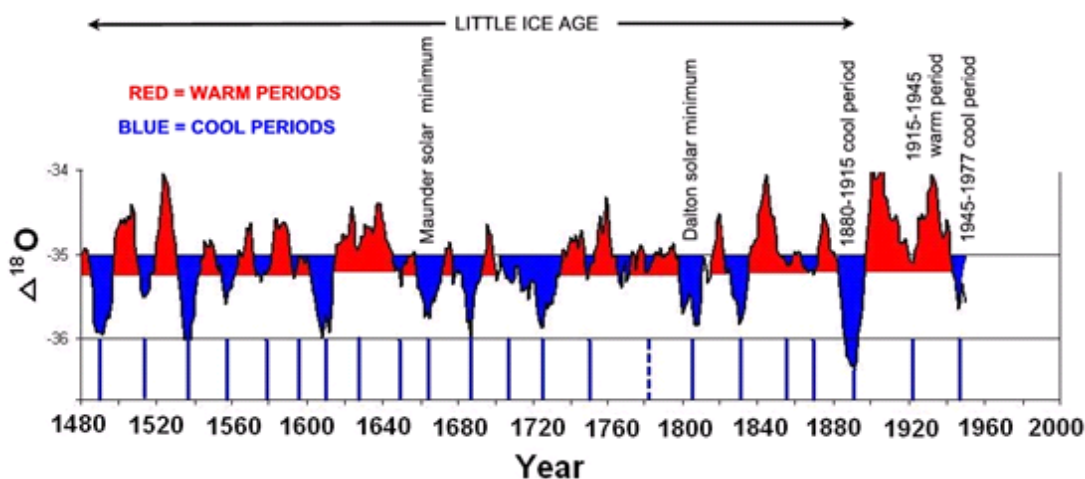


Figure 5.12.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460. Data from Grootes and Stuiver (1997). Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO₂ emissions as the primary source of global warming*. Elsevier.

Observations: The Cryosphere

extended for miles in every direction, closing many harbors; the population of Iceland decreased by half; and the Viking colonies in Greenland died out in the 1400s because food could no longer be grown there.

Conclusions

The rhythmic Holocene 1,500-year temperature changes recorded in the Greenland GISP2 ice core show the magnitude of global warming experienced during the twentieth century falls well within the bounds of previous natural variations. In addition, and especially apparent during late Holocene historical times, a multidecadal climate modulation is apparent that closely approaches the pattern observed also in the twentieth century temperature record. Because late twentieth century warming corresponded to warming limbs of both the multidecadal and the 1,500-year rhythms, it was not unexpected.

In essence, both the rate and magnitude of twentieth century warming are small compared to the magnitude of the profound natural climate reversals over the past 25,000 years (Figure 5.12.4). Most important in the context of the public debate about climate change, none of the larger late Pleistocene and Holocene climatic events were accompanied by any significant parallel change in atmospheric carbon dioxide level. The null hypothesis that twentieth century warming represents natural climate variation therefore remains valid.

References

- Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in the North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396.
- Easterbrook, D.J., Gosse, J., Sherard, C., Evenson, E., and Finkel, R. 2011. Evidence for synchronous climatic events: cosmogenic exposure ages of glaciations. Chapter 2 in Easterbrook, D.J. (Ed.) *Evidence-based Climate Science: Data Opposing CO₂ Emissions as the Primary Source of Global Warming*. Elsevier.
- Fagan, B. 2001. *The Little Ice Age: How climate made history 1300–1850*. Basic Books.
- Fagan, B. 2009. *The Great Warming: Climate change and the rise and fall of civilizations*. Bloomsbury Press.
- Grootes, P.M. and Stuiver, M. 1997. Oxygen 18/16 variability in Greenland snow and ice with 10³ to 10⁵-year time resolution. *Journal of Geophysical Research* **102**: 26,455–26,470.

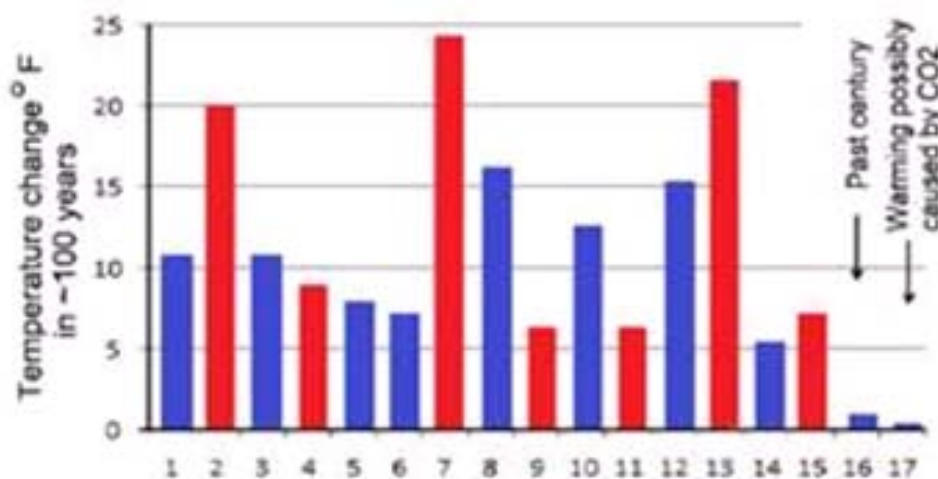


Figure 5.12.4. Magnitudes of the largest warming/cooling events over the past 25,000 years. Temperature changes shown on the vertical axis are rise or fall of temperatures in about a century. Event number 1 happened about 24,000 years ago, and event number 15 is about 11,000 years old. At least three warming events were 20 to 24 times the magnitude of warming over the past century, and four were six to nine times the magnitude of warming over the past century. The magnitude of the only modern warming which might possibly have been caused by CO₂ (1978–1998) is insignificant compared to the earlier periods of warming. Plotted from data in Cuffey and Clow (1997) and Alley (2000).

Climate Change Reconsidered II

Grove, J.M. 1988. *The Little Ice Age*. Methuen, London and New York.

Grove, J.M. 2004. *Little Ice Ages: Ancient and Modern*. Routledge, New York.

Oliver, J.E, 1973. *Climate and Man's Environment*. Wiley, NY.

Singer, F. and Avery, D. 2007. *Unstoppable Global Warming—Every 1500 Years*. Rowman and Littlefield.

Tkachuck, R.D. 1983. *The Little Ice Age*. Geoscience Research Institute. http://www.grisda.org/reports/or10_51.htm.

Wanner, H. and Butikofer, J. 2008. Holocene Bond cycles: real or imaginary? *Geografie-Sbornik Ceske Geograficke Spolecnosti* **113**: 338–350.

6

Observations: The Hydrosphere and Ocean

Willem de Lange (New Zealand)

Robert M. Carter (Australia)

Introduction

6.1. The Hydrosphere

Key Findings

6.1.1. Precipitation

6.1.2. Monsoons

6.1.3. Snow

6.1.4. Evaporation

6.1.5. Drought

6.1.6. Rivers and Streamflow

6.2. The Oceans

Key Findings

6.2.1. Sea Level Change

6.2.2. Ocean Heat

6.2.3. Ocean Circulation

Introduction

The hydrosphere comprises the combined mass of water that occurs on or near Earth's surface. It includes oceans, lakes, rivers, and streams. Because it covers about 70 percent of Earth's surface area, the hydrosphere plays a vital role in sustaining communities of water-inhabiting plants and animals.

The processes and characteristics of the hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, aspects of the hydrosphere also change in response to external climate change forcings, some of which are natural (e.g., changed solar insolation) and some of human origin (e.g.,

greenhouse gas forcing). This distinction between natural and anthropogenic forcings, which applies to all aspects of Earth's climate system, is easy to draw in principle, but in practice it has proved difficult to establish that any specific changes documented in the hydrosphere over the past century have their origins in human activity.

Near Earth's surface, precipitation of water out of the atmosphere occurs mostly in the forms of rain and snow. Hail contributes locally when conditions of strong, upward motion and freezing at lower levels of the atmosphere occur within passing thunderstorms and result in the formation of ice balls and lumps. The Northern and Southern Hemisphere monsoons are also precipitation-related phenomena, representing periods of particularly intense rainfall driven by

strong, seasonal, wind-induced movements of moisture-laden air off the ocean and onto an adjacent landmass.

At the same time, the patterns of evaporation that recycle water back to the atmosphere are heavily dependent upon both atmospheric and ocean temperature, which themselves vary in dynamic ways. Evaporation and precipitation are key processes that help determine the occurrence of rare meteorological events such as the storm bursts, cyclones, and deluges that feed catastrophic (from the human perspective) flooding; alternatively, the absence of precipitation can lead to equally catastrophic dryings and droughts.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC, 2007) paid much attention to the possibility human greenhouse-induced warming would lead to an increase in either or both the number and severity of extreme meteorological events. Subsequently, however, an IPCC expert working group (IPCC, 2012) has determined:

There is medium evidence and high agreement that long-term trends in normalised losses have not been attributed to natural or anthropogenic climate change. ... The statement about the absence of trends in impacts attributable to natural or anthropogenic climate change holds for tropical and extratropical storms and tornados. ... The absence of an attributable climate change signal in losses also holds for flood losses.

This chapter, building on the earlier conclusions of Idso and Singer (2009) and Idso *et al.* (2011), updates the Nongovernmental International Panel on Climate Change's (NIPCC) summary of the scientific literature on global warming as it might affect the hydrosphere. We again find changes in evaporation, precipitation, drought, ocean heat, ocean circulation, and sea level occur mostly in ways that contradict and rarely reinforce the claims of the IPCC and the projections of its models. Contrary to what has been feared would be caused by rising carbon dioxide levels, over the past 50 years there have been no CO₂-linked changes in precipitation patterns or river flows; signs exist of deceleration rather than acceleration of sea-level rise; and there have been no unnatural changes in the rate or pattern of Atlantic meridional overturning circulation (MOC).

References

Idso, C.D. and Singer, S.F. 2009. *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

Idso, C.D., Singer, S.F., and Carter, R.M. 2011. *Climate Change Reconsidered: 2011 Interim Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. Chicago, IL: The Heartland Institute.

IPCC 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., *et al.* (Eds.) Cambridge, UK: Cambridge University Press.

IPCC 2012. *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)*. <http://ipcc-wg2.gov/SREX/report/>.

6.1 The Hydrosphere

Key Findings

There appears to be nothing unusual about the extremes of wetness and dryness experienced during the twentieth century, or about recent changes in ocean circulation, sea level, or heat content, that would require atmospheric carbon dioxide forcing to be invoked as a causative factor. Natural variability in the frequency or intensity of precipitation extremes and sea-level change occurs largely on decadal and multidecadal time scales, and this variability cannot be discounted as a major cause of recent changes where they have occurred.

The main findings of Section 6.1, The Hydrosphere, are:

- **GLOBAL PRECIPITATION.** Theoretical climate models indicate atmospheric moisture will be enhanced in a warming world, and therefore global precipitation should have increased in the late twentieth century. Although the empirical evidence is not fully conclusive, it increasingly indicates no temperature-related intensification of the hydrological cycle has occurred recently over the global land surface.
- **REGIONAL PRECIPITATION.** From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events such as floods and droughts. Regional studies from around the

Observations: The Hydrosphere and Oceans

world in general fail to provide evidence of rising or more variable precipitation in the late twentieth century. These studies also show (1) ancient floods or droughts of at least the same magnitude as their modern counterparts occurred repetitively throughout the Holocene (last 10,000 years) and before; (2) decreased rainfall occurred during both climatically warm (Medieval Warm Period) and climatically cool (Little Ice Age) periods; (3) warming is sometimes accompanied by a reduction in precipitation-related weather extremes; (4) no evidence exists for a correlation between precipitation variability and atmospheric levels of CO₂; instead, studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, El Niño-Southern Oscillation, and solar variation implicated as controlling factors.

- **WATER RESOURCES.** Concern has been expressed that increasing concentrations of atmospheric CO₂ will adversely affect water resources. Nearly all water resource studies show just the opposite occurred during the late twentieth century warming, with moisture becoming more available.
- **MONSOONS.** Evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. Instead, the data sometimes suggest the opposite and overall suggest precipitation responds mostly to cyclical variations in solar activity. Both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period.
- **MONSOON MODELS.** Assessments of the predictive skill of monsoon models forced by CO₂ change unanimously find them to be inadequate. If climate models cannot accurately simulate the monsoonal precipitation that affects almost half the world's population, they cannot be relied upon as a basis for setting policy. A better understanding of the role of internal feedback processes as represented by the ENSO, PDO, AMO, solar, and other climatic indices is needed for improved forecasting of monsoon behavior.
- **SNOWFALL.** Studies from China above 40°N latitude demonstrate late twentieth century

warming was accompanied by an increase in winter snow depth, promoting increased vegetative growth in desert areas and grasslands and resulting in a reduction in sand-dust storms. These changes represent environmentally positive developments.

- **EVAPORATION.** Theoretical considerations suggest late twentieth century warming should have been accompanied by an increase in evaporation. Instead, direct measurements of pan evaporation show a reduction over the twentieth century. This reduction has been linked to reducing insolation (solar dimming) and wind stilling at ground level, caused by increasing cloud cover and atmospheric aerosols.
- **DROUGHT.** Drought represents moisture deficit, but the relationship between the occurrence of drought and global warming is, at best, weak. In some places severe droughts occurred during the Medieval Warm Period, and in others severe droughts failed to occur during the late twentieth century warming. The evidence suggests the recent warming in particular, and drought in general, are the result of factors other than anthropogenic CO₂ emissions.
- **STREAMFLOW.** Many authors claim global warming will lead to the intensification of the hydrological cycle and the global occurrence of more floods. Few real-world data support this speculation. Neither global nor regional changes in streamflow can be linked to CO₂ emissions. Moreover, most recent changes in streamflow have been either not deleterious or beneficial—often extremely so. Some studies have identified solar factors or multidecadal cyclicity as more important influences on streamflow variability than is atmospheric CO₂.

6.1.1 Precipitation

All forms of precipitation are dynamic, occurring or not occurring in response to changing atmospheric conditions (especially heat and water vapor) on a minute-by-minute, hourly, daily, weekly, or seasonal basis. Regarding the potential effect of global warming on these patterns, Huntington (2006) has noted there is “a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al.*,

1991; Loaciga *et al.*, 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al.*, 2001).” In reviewing the scientific literature on recent patterns of precipitation, Huntington concluded on a globally averaged basis, precipitation over land had indeed increased by about 2 percent over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998).

In keeping with this result, model predictions of CO₂-induced global warming often suggest warming should be accompanied by increases in rainfall. For example, Rawlins *et al.* (2006) state, after the *Arctic Climate Impact Assessment* (2005), “warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation.” Peterson *et al.* (2002) noted “both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature,” citing Manabe and Stouffer (1994) and Rahmstorf and Ganopolski (1999). Similarly, Kunkel (2003) says “several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998).” To date, global circulation models (GCMs) have failed to accurately reproduce observed patterns and totals of precipitation (Lebel *et al.*, 2000).

Moise *et al.* (2012) analyzed the changes in tropical Australian climate projected by 19 CMIP3 coupled models for the IPCC’s A2 scenario over the twenty-first century. While equatorial regions to the north of Australia are projected to have increased precipitation during austral summer (December to February) by the end of the twenty-first century, there is no significant change over northern Australia itself, based on the model ensemble mean. There is a large spread in model simulations of precipitation change, with both large positive and negative anomalies. The ensemble mean change in the seasonal cycle of precipitation over tropical Australia is nonetheless small, with precipitation increase during March and April, suggesting a prolonged Australian wet season.

No model consensus exists on how interannual variability of tropical Australian precipitation will change in the future, although more models simulate increased variability than decreased. Correlations between full wet season (October to April) precipitation and austral spring (September to November) NINO 3.4 sea surface temperature anomalies show a slight weakening. The spread in projected precipitation seasonal cycle changes between simulations from the same model is larger

than the inter-model range, indicating large internal or natural variability in tropical Australian precipitation relative to the climate change signal. Zonal wind changes indicate an intensification of austral summer low level westerlies combined with a weakening of upper easterlies. Low level westerlies also persist for longer periods of time, consistent with a delay in the monsoon retreat.

All models simulate an increase in the land-ocean temperature contrast in austral summer, with a significant correlation between changes in land-ocean temperature contrast in the pre-monsoon (austral spring) and summer precipitation changes. Analysis of precipitation changes using regime-sorting techniques shows offsetting tendencies from thermodynamic changes associated with enhanced atmospheric moisture and dynamic changes associated with a weakened atmospheric circulation.

Conclusions

We are thus confronted with a dilemma: Although the theoretical expectation, supported by modeling, is that global warming should result in enhanced atmospheric moisture, empirical results often show otherwise. Many scientists are now examining historical precipitation records in an effort to determine how temperature changes of the past have affected Earth’s hydrologic cycle. In the following sections, we review what these studies have revealed about patterns of precipitation, region by region across the globe.

References

- Arctic Climate Impact Assessment (ACIA). 2005. <http://www.amap.no/arctic-climate-impact-assessment-acia>.
- Arnell, N.W., Liu, C., Compagnucci, R., da Cunha, L., Hanaki, K., Howe, C., Mailu, G., Shiklomanov, I., and Stakhiv, E. 2001. Hydrology and water resources. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (Eds.). *Climate Change 2001: Impacts, Adaptation and Vulnerability, The Third Assessment Report of Working Group II of the Intergovernmental Panel on Climate Change*, Cambridge, University Press, Cambridge, UK, pp. 133–191.
- Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S., and Yap, K.S. 2001. Projections of future climate change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (Eds.). *Climate Change 2001: The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the*

Observations: The Hydrosphere and Oceans

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Dai, A., Fung, I.Y., and DelGenio, A.D. 1997. Surface observed global land precipitation variations during 1900–1998. *Journal of Climate* **10**: 2943–2962.

DelGenio, A.D., Lacis, A.A., and Ruedy, R.A. 1991. Simulations of the effect of a warmer climate on atmospheric humidity. *Nature* **351**: 382–385.

Held, I.M. and Soden, B.J. 2000. Water vapor feedback and global warming. *Annual Review of Energy and Environment* **25**: 441–475.

Hulme, M., Osborn, T.J., and Johns, T.C. 1998. Precipitation sensitivity to global warming: comparisons of observations with HadCM2 simulations. *Geophysical Research Letters* **25**: 3379–3382.

Huntington, T.G. 2008. Can we dismiss the effect of changes in land-based water storage on sea-level rise? *Hydrological Processes* **22**: 717–723.

Kharin, V.V. and Zwiers, F.W. 2000. Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *Journal of Climate* **13**: 3670–3688.

Kunkel, K.E. 2003. North American trends in extreme precipitation. *Natural Hazards* **29**: 291–305.

Lebel, T., Delclaux, F., Le Barbé, L., and Polcher, J. 2000. From GCM scales to hydrological scales: rainfall variability in West Africa. *Stochastic Environmental Research and Risk Assessment* **14**: 275–295.

Loaciga, H.A., Valdes, J.B., Vogel, R., Garvey, J., and Schwarz, H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* **174**: 83–127.

Manabe, S. and Stouffer, R.J. 1994. Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *Journal of Climate* **7**: 5–23.

Moise, A.F., Colman, R.A., and Brown, J.R. 2012. Behind uncertainties in projections of Australian tropical climate: Analysis of 19 CMIP3 models. *Journal of Geophysical Research: Atmospheres* **117** (D10): D10103. doi:10.1029/2011JD017365.

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* **298**: 2171–2173.

Rahmstorf, S. and Ganopolski, A. 1999. Long-term global warming scenarios computed with an efficient coupled climate model. *Climatic Change* **43**: 353–367.

Rawlins, M.A., Willmott, C.J., Shiklomanov, A., Linder, E., Frolking, S., Lammers, R.B., and Vorosmarty, C.J. 2006. Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean. *Geophysical Research Letters* **33**: 10.1029/2005GL025231.

Trenberth, K.E. 1998. Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change* **39**: 667–694.

Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* **42**: 327–339.

Yonetani, T. and Gordon, H.B. 2001. Simulated changes in the frequency of extremes and regional features of seasonal/annual temperature and precipitation when atmospheric CO₂ is doubled. *Journal of Climate* **14**: 1765–1779.

Zwiers, F.W. and Kharin, V.V. 1998. Changes in the extremes of climate simulated by CCC GCM2 under CO₂-doubling. *Journal of Climate* **11**: 2200–2222.

6.1.1.1. Global

From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events, such as floods and droughts. Nonetheless, some researchers have attempted to address the issue at a global level, as represented by the following studies.

New *et al.* (2001) reviewed several global precipitation datasets and summarized precipitation patterns since the late nineteenth century. They determined precipitation over land fell mostly below the century-long mean over the first 15 years of the record but increased from 1901 to the mid-1950s, remained above the century-long mean until the 1970s, and declined by about the same amount thereafter up to 1992 (taking it well below the century-long mean), before recovering to edge upward towards the century mean. For the entire century there was a slight increase in global land area precipitation, but after 1915 there was essentially no net change.

New *et al.* also studied the oceanic portion of the world between 30°N and 30°S, the precipitation record for which begins in 1920. They found an overall decrease of about 0.3 percent per decade. For the planet as a whole, which is 70 percent covered by water, there probably has been a slight decrease in precipitation since about 1917.

Neng *et al.* (2002) analyzed more recent

precipitation data, from 1948 to 2000, to determine the effect of warm ENSO years on annual precipitation over the land area of the globe. Although some regions experienced more rainfall in warm ENSO years, others experienced less. “In warm event years, the land area where the annual rainfall was reduced is far greater than that where the annual rainfall was increased, and the reduction is more significant than the increase.” This result conflicts with GCM model projections.

Smith *et al.* (2006) used empirical orthogonal function (EOF) analysis to study annual precipitation variations over 26 years beginning in 1979 using a database from the Global Precipitation Climatology Project (GPCP), which produces a merged satellite and *in situ* global precipitation estimate (Huffman *et al.*, 1997; Adler *et al.*, 2003). The first three EOFs determined accounted for 52 percent of the observed variance in the precipitation data. Mode 1 was associated with mature ENSO conditions and correlated strongly with the Southern Oscillation Index, whereas Mode 2 was associated with the strong warm ENSO episodes of 1982/83 and 1997/98. Mode 3 was uncorrelated with ENSO but associated with changes in interdecadal warming of tropical sea surface temperatures, including increased precipitation over the tropical Pacific and Indian Oceans associated with local ocean warming. This increased precipitation was “balanced by decreased precipitation in other regions,” so “the global average change [was] near zero.”

Ault *et al.* (2012) summarized the application of GCMs to precipitation analysis, acknowledging “the last generation of models, those comprising [the] Climate Model Intercomparison Project III (CMIP3) archive, was unable to capture key statistics characterizing decadal to multidecadal (D2M) precipitation fluctuations” and “CMIP3 simulations overestimated the magnitude of high frequency fluctuations and consequently underestimated the risk of future decadal-scale droughts.

Ault *et al.* then used the Climate Model Intercomparison Project 5 (CMIP5) network to evaluate the ability of these models to simulate twentieth century variability. Their analyses were conducted using gridded (2.5 x 2.5) version 4 reanalysis product data available from the Global Precipitation Climatology Centre (Rudolf *et al.*, 2005), which spans the period January 1901 through December 2007. They found “CMIP5 simulations of the historical era (1850–2005) underestimate the importance [of] D2M variability in several regions where such behavior is prominent and linked to

drought,” namely, “northern Africa (e.g., Giannini *et al.*, 2008), Australia (Kiem and Franks, 2004; Verdon *et al.*, 2004; Leblanc *et al.*, 2012), western North America (Seager, 2007; Overpeck and Udall, 2010), and the Amazon (Marengo *et al.*, 2011).”

Ault *et al.* further state “the mismatch between 20th century observations and simulations suggests model projections of the future may not fully represent all sources of D2M variations,” noting “if observed estimates of decadal variance are accurate, then the current generation of models depict D2M precipitation fluctuations that are too weak, implying that model hindcasts and predictions may be unable to capture the full magnitude of realizable D2M fluctuations in hydroclimate.” As a result, “the risk of prolonged droughts and pluvials in the future may be greater than portrayed by these models.”

Sun *et al.* (2012) analyzed monthly precipitation observations from 1940–2009 for the global land surface, having assessed the ocean precipitation data as unreliable for trend analyses. They found a near-zero trend in decadal mean precipitation, a finding consistent with earlier studies that found little variation in global mean precipitation at periods longer than the turnover time for water in the atmosphere (~10 days). They did, however, find a reduction in the global land precipitation variation, such that wet areas became drier and dry areas became wetter. This finding directly contradicts the expectation (Section 6.1.6) that there would be an intensification of the hydrological cycle (i.e., wet areas get wetter and dry areas get drier as stated by Trenberth (2011). Sun *et al.* also found, with respect to monthly precipitation variance (an indicator of extreme precipitation), there was “no relationship to local ... or global changes in temperature.”

References

- Adler, R.F., Susskind, J., Huffman, G.J., Bolvin, D., Nelkin, E., Chang, A., Ferraro, R., Gruber, A., Xie, P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., and Arkin, P. 2003. The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979-present). *Journal of Hydrometeorology* 4: 1147–1167.
- Ault, T.R., Cole, J.E., and St. George, S. 2012. The amplitude of decadal to multidecadal variability in precipitation simulated by state-of-the-art climate models. *Geophysical Research Letters* 39: 10.1929/2012GL053424.
- Giannini, A., Biasutti, M., Held, I.M., and Sobel, A.H. 2008. A global perspective on African climate. *Climatic Change* 90: 359–383.

Observations: The Hydrosphere and Oceans

Huffman, G.J., Adler, R.F., Chang, A., Ferraro, R., Gruber, A., McNab, A., Rudolf, B., and Schneider, U. 1997. The Global Precipitation Climatology Project (GPCP) combined data set. *Bulletin of the American Meteorological Society* **78**: 5–20.

Kiem, A.S. and Franks, S.W. 2004. Multi-decadal variability of drought risk, eastern Australia. *Hydrological Processes* **18**, 2039–2050.

Leblanc, M., Tweed, S., Van Dijk, A., and Timbal, B. 2012. A review of historic and future hydrological changes in the Murray-Darling Basin. *Global and Planetary Change* **80-81**: 226–246.

Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., and Rodriguez, D.A. 2011. The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters* **38**: 10.1029/2011GL047436.

Neng, S., Luwen, C., and Dongdong, X. 2002. A preliminary study on the global land annual precipitation associated with ENSO during 1948–2000. *Advances in Atmospheric Sciences* **19**: 993–1003.

New, M., Todd, M., Hulme, M., and Jones, P. 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology* **21**: 1899–1922.

Overpeck, J. and Udall, B. 2010. Dry times ahead. *Science* **328**: 1642–1643.

Roderick, M.L. and Farquhar, G.D. 2012. Changes in the variability of global land precipitation. *Geophysical Research Letters* **39** (19): L19402. doi:10.1029/2012GL053369.

Rudolf, B., Beck, C., Grieser, J., and Schneider, U. 2005. *Global Precipitation Analysis Products of Global Precipitation Climatology Centre (GPCC)*. Technical Report. Dtsch. Wetterdienst, Offenbach, Germany.

Seager, R. 2007. The turn of the century North American drought: Global context, dynamics, and past analogs. *Journal of Climate* **20**: 5527–5552.

Smith, T.M., Yin, X., and Gruber, A. 2006. Variations in annual global precipitation (1979–2004), based on the Global Precipitation Climatology Project 2.5° analysis. *Geophysical Research Letters* **33**: 10.1029/2005GL025393.

Sun, F., Farquhar, G.D., and Roderick, M.L. 2012. Changes in the variability of global land precipitation. *Geophysical Research Letters*: doi:10.1029/2012GL053369.

Trenberth, K.E. 2011. Changes in precipitation with climate change, *Climate Research* **47(1-2)**: 123–138. 10.3354/cr00953.

Verdon, D.C., Wyatt, A.M., Kiem, A.S., and Franks, S.W.

2004. Multidecadal variability of rainfall and streamflow: Eastern Australia. *Water Resources Research* **40**, W10201. <http://dx.doi.org/10.1029/2004WR003234>.

Earlier Research

Other important studies of rainfall changes, at the regional rather than global level, include the following:

- Stankoviansky (2003) used maps, aerial photographs, field geomorphic investigation, and historical documentation to determine the spatial distribution and history of gully landforms in Myjava Hill Land, Slovakia (near the Czech Republic western border). Stankoviansky found “the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s, and the second between the 1780s and 1840s. Though gullying was caused by the extensive forest clearances undertaken to expand farmland, the triggering mechanism was extreme rainfalls during the Little Ice Age.” Stankoviansky concluded “the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age”; he also noted destructive rainfall events were much more common during the Little Ice Age than thereafter “is often regarded as generally valid for Central Europe.” In other words, this empirical evidence shows cooling rather than warming results in greater precipitation.

- Giambelluca *et al.* (2008) and Chu *et al.* (2010) undertook assessments of whether warming at a rate of 0.163°C/decade, as experienced recently in Hawaii, was associated with additional rainfall. Five climate change indices for extreme precipitation were calculated from daily observational records between the 1950s and 2007: a simple daily intensity index, the total number of days with precipitation ≥ 25.4 mm, the annual maximum consecutive five-day precipitation amount, the fraction of annual total precipitation from events that exceeded the 1961–1990 95th percentile, and the number of consecutive dry days. Chu *et al.* documented a change in the types of precipitation intensity since the 1980s, with more frequent light precipitation and less frequent moderate and heavy precipitation, as well as a “shorter annual number of days with intense precipitation and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events

exceeding the 1961–1990 95th percentile in the recent epoch [1980–2007] relative to the first epoch [1950–1979].” IPCC predictions for more precipitation to occur with Hawaiian warming are incorrect; in fact, the opposite occurred.

- Diodato *et al.* (2008) studied erosive rainfall in the Calore River Basin (Southern Italy) using combined data from 425-year-long series of observations (1922–2004) and proxy-based reconstructions (1580–1921). Interdecadal variability was strong, with multidecadal erosional peaks reflecting the behavior of the mixed population of thermo-convective and cyclonic rainstorms that occurred. Like Stankoviansky (2003), they found the “Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall.”

- Xu *et al.* (2008) analyzed 50 years (1957–2006) of upper-air Chinese radiosonde observations, along with parallel surface air temperature and precipitation data. In the summer half of the year, they found, “the Tibetan Plateau acts as a strong ‘dynamic pump’ [that] continuously attracts moist air from the low-latitude oceans.” When reaching the plateau, some of these flows rise along its south side and cause “frequent convections and precipitations,” which feed its mid- and low-latitude glaciers, snow-packs, and lakes, from whence originate many of Asia’s major rivers. This flow system constitutes the largest river runoff from any single location in the world. The Tibetan Plateau has been called the “world’s water tower” because of the strong influence it exerts on northern hemisphere mid-latitude moisture, precipitation, and runoff.

In further analysis of their datasets, the four researchers found recent warming in the plateau started in the early 1970s, and the water vapor content showed an upward trend from the early 1980s and continues to the present time, a pattern similar to that found in the annual precipitation data.

- A longer climate history for the Tibetan Plateau for the past 1,700 years was developed by Zhao *et al.* (2009) based upon carbonate percentages and ostracod abundances in sediment cores from Hurlig Lake in the arid Northeast Tibetan Plateau. They compared those records with a contemporaneous history of precipitation derived from tree-ring analysis and changes in solar activity manifest in solar proxy residual $\Delta^{14}\text{C}$ data.

Zhao *et al.* discovered carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the past 1,000

years. Cross-spectral analysis between the moisture proxies and solar activity proxy showed high coherence at the ~200-year periodicity. This correlation also is found with Chinese monsoon intensity records and implies the possible solar forcing of moisture oscillations in the NE Tibetan Plateau. In addition, the inverse relationship between the moisture pattern in the Qaidam Basin and tree-ring-based monsoon precipitation in the surrounding mountains suggests “topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region.”

- Kim *et al.* (2009) analyzed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006) to assess drought severity using four indices: the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), described as “an intensive measure that considers daily water accumulation with a weighting function for time passage”; a Corrected EDI (CEDI) that “considers the rapid runoff of water resources after heavy rainfall”; an Accumulated EDI (AEDI) that “considers the drought severity and duration of individual drought events”; and a year-accumulated negative EDI (YAEDI) “representing annual drought severity.”

The researchers’ precipitation history and two of their drought severity histories are presented, in that order, in Figures 6.1.1.1.1 and 6.1.1.1.2. It is apparent the only major deviation from long-term normality is the decadal-scale decrease in precipitation and ensuing drought around AD 1900. Neither the last part of the Little Ice Age during the early nineteenth century nor the onset of high carbon dioxide emissions after about 1950 appears to exercise any effect on precipitation or drought in Korea, and similar results are known from around the world.

Conclusions

Although Huntingdon (2006) concluded the evidence on balance was consistent with an ongoing and future intensification of the global hydrological cycle, he acknowledged considerable uncertainties and noted the evidence did not support the likelihood of increasingly frequent and intense tropical storms and floods. Since his review, the evidence remains mixed but increasingly indicates no temperature-related intensification of the hydrological cycle has been observed for the global land surface. Although the data show no global trend indicative of land precipitation intensification, spatial and temporal variations can result in regional trends.

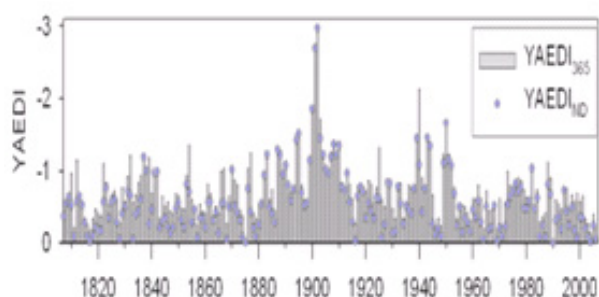


Figure 6.1.1.1.1. Annual “dryness” history at Seoul, Korea, 1807-2006, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDI10 (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

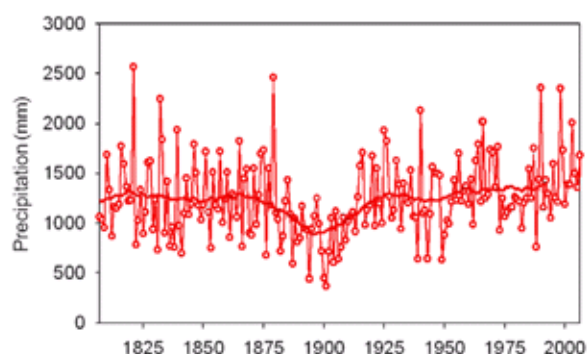


Figure 6.1.1.1.2. Annual precipitation history at Seoul, Korea; solid line, 30-year moving-average. Adapted from Kim *et al.* (2009).

References

- Byun, H.R. and Wilhite, D.A. 1999. Objective quantification of drought severity and duration. *Journal of Climate* **12**: 2747–2756.
- Chu, P.-S., Chen, Y.R., and Schroeder, T.A. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**: 4881–4900.
- Diodato, N., Ceccarelli, M., and Bellocchi, G. 2008. Decadal and century-long changes in the reconstruction of erosive rainfall anomalies in a Mediterranean fluvial basin. *Earth Surface Processes and Landforms* **33**: 2078–2093.

Giambelluca, T.W., Diaz, H.F., and Luke, M.S.A. 2008. Secular temperature changes in Hawaii. *Geophysical Research Letters* **35**: 10.1029/2008GL034377.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* **319**: 83–95.

Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

Stankoviansky, M. 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. *Catena* **51**: 223–239.

Xu, S., Lu, C., Shi, X., and Gao, S. 2008. World water tower: An atmospheric perspective. *Geophysical Research Letters* **35**: 10.1029/2008GL035867.

Zhao, C., Yu, Z., Zhao, Y., and Ito, E. 2009. Possible orographic and solar controls of Late Holocene centennial-scale moisture oscillations in the northeastern Tibetan Plateau. *Geophysical Research Letters* **36**: 10.1029/2009GL040951.

6.1.1.2. Africa

South Africa has one of the most comprehensive hydro-meteorological databases in the world. Remarkably, 40 years before the establishment of the IPCC, civil engineer D.F. Kokot (1948) published a report for the S.A. Department of Irrigation that found no evidence of a general decrease in the historical records of rainfall or river flow and concluded therefore no link existed between climate change and rainfall over South Africa, a conclusion confirmed by van der Merwe *et al.* (1951).

In the north of Africa another civil engineer, H.E. Hurst, analyzed 1,080 years of flow data from the Nile River for the period 641 to 1946 as part of storage capacity studies for the proposed Aswan High Dam (Hurst, 1951, 1954). He found an unexplained anomaly in the data, also present in other long meteorological (temperature, rainfall) and proxy (lake sediment cores, tree ring) records, which Alexander (1978) identified as related to a 20-year (later, 21-year) periodicity; i.e. to the Hale double sunspot cycle. It thereby became apparent South African periods of flood and drought occurred in a predictable way, rather than occurring at random as had been conventionally believed. The starts of drier and wetter periods are readily identified, characterized by sudden reversals from sequences of years with low rainfall (droughts) to sequences of years with wide-spread

rainfall and floods. It is not the simple sum of annual sunspot numbers (Figure 6.1.1.2.1, top graph) that are in synchrony with river flows plotted as the annual departure from the mean (Figure 6.1.1.2.1, fourth graph), but rather the rate of change in sunspot numbers (Figure 6.1.1.2.1, second graph).

Will Alexander, professor of civil engineering at the University of Pretoria, later published several pivotal papers and reports (e.g., Alexander 1995, 2005, 2006; Alexander *et al.*, 2004) that greatly increased our understanding of flood-drought cycling in southern Africa and established the importance of solar influence. In his 1995 paper, published just before the end of the severe drought that accompanied cycle G, Alexander predicted the oncoming flood period (G).

Alexander points out nearly all previous analyses of rainfall patterns have been based on the assumption that data for annual rainfall, river flow, and flood peak maxima are independent, identically distributed, and form stationary time series. All three assumptions are wrong.

Detailed, high-quality hydrological datasets from South Africa show instead annual values are sequentially independent but not serially independent; sequential values are not identically distributed as both their mean values as well as their distribution about the mean change from year to year in 21-year sequences; and the series are not stationary in time because of the presence of statistically significant 21-year serial correlation. These properties are related to a synchronous linkage with solar activity, as first reported more than 100 years ago by Hutchins (1889). Later studies by Spate *et al.* (2004) and Whiting *et al.* (2004) also demonstrate flood spate flows in Southern Africa occur on a multidecadal rhythm closely linked to the El Niño-Southern Oscillation.

Conclusions

Alexander *et al.* (2007) explain the significance of this pivotal research:

It is extremely important that all those involved with water resource studies should appreciate that there are fundamental flaws in current global climate models used for climate change applications. These models fail to accommodate the statistically significant, multiyear periodicity in the rainfall and river flow data observed and reported by South African scientists and engineers for more than the past 100 years. They also failed to predict the recent climate reversals based on Alexander's model (Alexander 1995, 2005). The

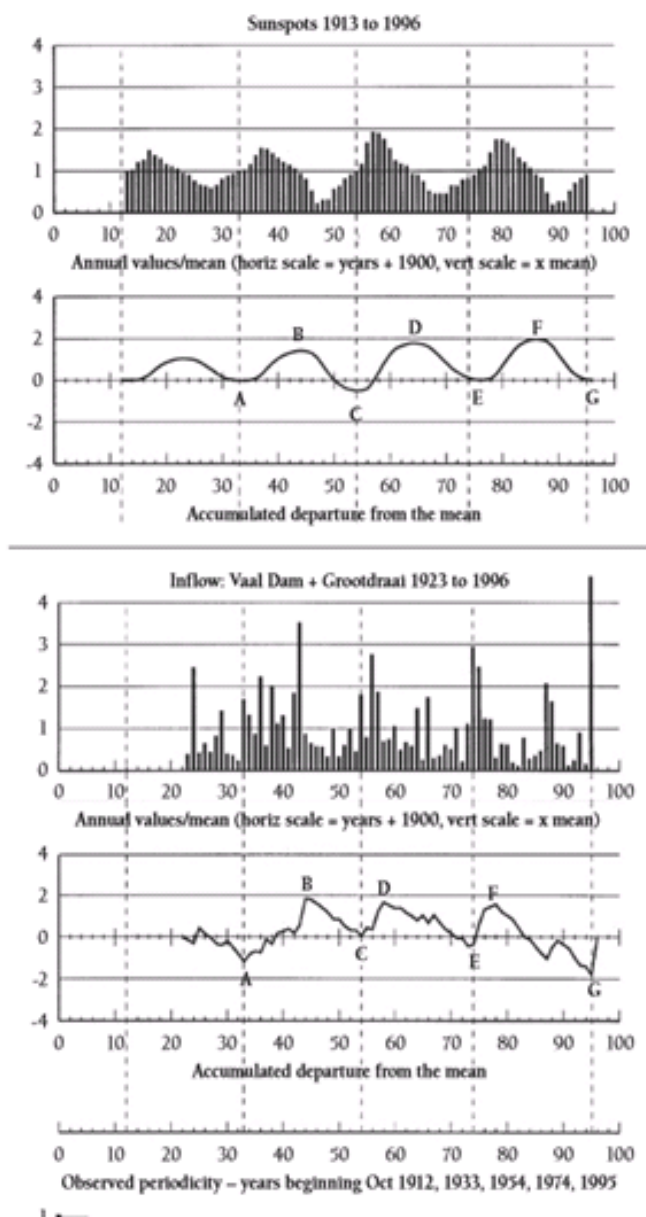


Figure 6.1.1.2.1. Comparison of the characteristics of annual sunspot numbers with corresponding characteristics of annual flows in the Vaal River, South Africa. Adapted from Alexander, W.J.R., Bailey, F., Bredenkamp, D.B., van der Merwe, A., and Willemse, N. 2007. Linkages between solar activity, climate practicability and water resource development. *Journal of the South African Institution of Civil Engineering* 49: 32–44, Figure 7.

global climate model outputs can therefore not be used for adaptation studies.

Koutsoyiannis (2013) has argued the multiscale change in flow records in the Nile, first recorded by

Observations: The Hydrosphere and Oceans

Hurst and then further analyzed by Alexander and others, indicates long-term flow changes relevant to water engineering are much more frequent and intense than commonly perceived. Accordingly, future system states are much less certain and predictable on long time scales than is implied by standard methods of statistical analysis. From Koutsoyiannis argues a change of perspective is needed, in which change and uncertainty form essential parts of future hydrological analyses.

References

Alexander, W.J.R. 1978. *Long range prediction of river flow—a preliminary assessment*. Department of Water Affairs Technical Report TR 80.

Alexander, W.J.R. 1995. Floods, droughts and climate change. *South African Journal of Science* **9**: 403–408

Alexander, W.J.R. 2005. Development of a multi-year climate prediction model. *Water SA* 31(2). Available at <http://www.wrc.org.za/downloads/watersa/205/Apr-05/1788.pdf>.

Alexander, W.J.R. 2006. *Climate change and its consequences—an African perspective*. Technical report submitted to the South African Water Commission, 473 pp, 38 figures, 51 tables.

Alexander, W.J.R., Bailey, F., Bredenkamp, D.B., van der Merwe, A., and Willemse, N. 2007. Linkages between solar activity, climate practicability and water resource development. *Journal of the South African Institution of Civil Engineering* **49**: 32–44.

Hurst, H.E. 1951. Long-term storage capacity of reservoirs. *Transactions of the American Society of Civil Engineers*, Paper 2447.

Hurst, H.E. 1954. Measurement and utilisation of the water resources of the Nile Basin. *Proceedings of the Institution of Civil Engineers, volume 3*, part III, pp 1–26, April 1954: discussions pp 26–30, correspondence pp 580–594.

Hutchins, D.E. 1889. Cycles of drought and good seasons in South Africa. *Wynberg Times*, Steam Printing Office.

Kokot D.F. 1948. An investigation into the evidence bearing on recent climatic changes over southern Africa. Irrigation Department Memoir.

Koutsoyiannis, D. 2012. Hydrology and change. *Hydrological Sciences Journal* **58**: 1–21; doi: 10.1080/02626667.2013.804626.

Van der Merwe, C.R., Acocks, J.P.H., Brain, C.K., Frommurze, H.F., Kokot, D.F., Schumann, T.E.W., and Tidmarsh C.E.M. 1951. *Report of the Desert Encroachment Committee appointed by the Minister of Agriculture*. Government Printer (U.G. 59/1951).

Whiting, J.P., Lambert, M.F., Metcalfe, A.V., Adamson, P.T., Franks, S.W., and Kuczera, G. 2004. Relationships between the El-Nino southern oscillation and spate flows in southern Africa and Australia. *Hydrology and Earth System Sciences* **8**: 1118–1128.

Earlier Research

Other significant recent papers on African precipitation patterns include the following:

- In two contextual studies, Lee-Thorp *et al.* (2001) described repeated rapid climate shifts in Southern Africa since the middle Holocene, and Verschuren *et al.* (2000) examined hydrologic conditions in equatorial East Africa over the past one thousand years. Verschuren *et al.* report the region was significantly drier than today during the Medieval Warm Period (AD 1000–1270) and relatively wetter than today during the Little Ice Age (AD 1270–1850). The LIA wetting was interrupted by three episodes of drought in 1390–1420, 1560–1625, and 1760–1840, which were “more severe than any recorded drought of the twentieth century.”

- The late eighteenth/early nineteenth century dry period in East Africa also was identified in West Africa by Nicholson (2001). She reports the most significant climatic change over the past 200 years has been “a long-term reduction in rainfall in the semi-arid regions of West Africa,” by as much as 20 to 40 percent in parts of the Sahel. There have been, she says, “three decades of protracted aridity” and “nearly all of Africa has been affected ... particularly since the 1980s.” Nicholson further notes dry conditions similar to those that have affected nearly all of Africa since the 1980s are not unprecedented; “a similar dry episode prevailed during most of the first half of the 19th century.”

- Nicholson and Yin (2001) report there have been two starkly contrasting climatic episodes in equatorial East Africa since the late 1700s. The first, which began prior to 1800, was characterized by “drought and desiccation.” Extremely low lake levels were the norm as drought reached its extreme during the 1820s and 1830s. In the mid to latter part of the 1800s, the drought began to weaken and floods became “continually high.” By the turn of the century, lake levels began to fall as mild drought conditions returned. The drought did not last long, and the latter half of the twentieth century has seen an enhanced hydrologic cycle with a return of some lake levels to the high stands of the mid to late 1800s.

- Richard *et al.* (2001) analyzed summer (January–March) rainfall totals in southern Africa over the

period 1900–1998, finding interannual variability was higher for the periods 1900–1933 and 1970–1998 but lower for the period 1934–1969. The strongest rainfall anomalies (greater than two standard deviations) were observed at the beginning of the century. The authors conclude there were no significant changes in the January–March rainfall totals nor any evidence of abrupt shifts during the twentieth century.

Conclusions

Three conclusions can be drawn from the African rainfall data.

- The recent much-commented recent drying in the Sahel is not in itself evidence of human-caused warming, because similar dry periods occurred periodically during the recent past.
- There is no established relationship between rainfall trends or changes in Africa and increased atmospheric carbon dioxide during the second half of the twentieth century.
- Contrary to some climate model projections, decreased rainfall can occur during both climatically warm (MWP) and climatically cool (LIA) times.

References

Lee-Thorp, J.A., Holmgren, K., Lauritzen, S.-E., Linge, H., Moberg, A., Partridge, T.C., Stevenson, C., and Tyson, P.D. 2001. Rapid climate shifts in the southern African interior throughout the mid to late Holocene. *Geophysical Research Letters* **28**: 4507–4510.

Nicholson, S.E. 2001. Climatic and environmental change in Africa during the last two centuries. *Climate Research* **17**: 123–144.

Nicholson, S.E. and Yin, X. 2001. Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. *Climatic Change* **48**: 387–398.

Richard, Y., Fauchereau, N., Pocard, I., Rouault, M., and Trzaska, S. 2001. 20th century droughts in southern Africa: Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *International Journal of Climatology* **21**: 873–885.

Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

6.1.1.3. Mediterranean

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Mediterranean region include the following:

- Rodrigo *et al.* (2000, 2001) reconstructed a seasonal rainfall record for 1501–1997 for Andalusia (southern Spain), and established a relationship exists with the North Atlantic Oscillation (NAO) over the period 1851–1997. Their research established the NAO index correlation with climate is strongest in winter, when it explains 40 percent of the total variance in precipitation. Rodrigo *et al.* stress “the recent positive temperature anomalies over western Europe and recent dry winter conditions over southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s,” as opposed to an intensification of global warming.
- Crisci *et al.* (2002) analyzed rainfall data from 81 gauges throughout Tuscany (central Italy) for three periods: from the beginning of each record through 1994; a shorter 1951–1994 period; and a still-shorter 1970–1994 period. For each of these periods, trends were derived for extreme rainfall durations of 1, 3, 6, 12, and 24 hours.

For the period 1970–1994, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested. For the longer 1951–1994 period, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations and one had negative trends at all durations. For the still-longer complete period of record, the majority of all stations again exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations, and one had negative trends at all durations. Such global warming as may have occurred during the twentieth century clearly had no impact on Italian rainfall.

- Tomozeiu *et al.* (2002) performed a series statistical tests to investigate the nature and potential causes of trends in winter (December–February) mean precipitation recorded at 40 stations in Northern Italy over the period 1960–1995. Nearly all stations experienced significant decreases in winter precipitation over the 35-year period of study, and a Pettitt test indicated a significant downward shift at all stations around 1985. An Empirical Orthogonal Function analysis revealed a principal component

Observations: The Hydrosphere and Oceans

representing the North Atlantic Oscillation (NAO), as found also by Rodrigo *et al.* (2001), suggesting the changes in winter precipitation around 1985 “could be due to an intensification of the positive phase of the NAO.”

- Sousa and Garcia-Murillo (2003) studied proxy indicators of climatic change, including precipitation, in Doñana Natural Park in Andalusia (southern Spain) for a period of several hundred years and compared their results with those of other researchers. The work revealed the Little Ice Age (LIA) was non-uniform and included periods both wetter and drier than average. Nevertheless, they cite Rodrigo *et al.* (2000) as indicating “the LIA was characterized in the southern Iberian Peninsula by increased rainfall” and Grove (2001) as indicating “climatic conditions inducing the LIA glacier advances [of Northern Europe] were also responsible for an increase in flooding frequency and sedimentation in Mediterranean Europe.” Sousa and Garcia-Murillo’s research complements the others’ work, finding “an aridization of the climatic conditions after the last peak of the LIA (1830–1870),” suggesting much of Europe became drier, not wetter, as Earth passed out of the Little Ice Age.

- Alexandrov *et al.* (2004) analyzed a number of twentieth century datasets from throughout Bulgaria and found “a decreasing trend in annual and especially summer precipitation from the end of the 1970s”; they note “variations of annual precipitation in Bulgaria showed an overall decrease.” In addition, the region stretching from the Mediterranean into European Russia and the Ukraine “has experienced decreases in precipitation by as much as 20% in some areas.”

- Touchan *et al.* (2005) used tree-ring data to develop summer (May–August) precipitation reconstructions for eastern Mediterranean (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back as much as 600 years. The research showed summer precipitation varied on multiannual and decadal timescales but without any overall long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods in 1601–1605 and 1751–1755. Both extreme wet and dry precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930.

- Clarke and Rendell (2006) analyzed 50 years of rainfall records (1951–2000) from eastern Basilicata (southern Italy) and compared them with the occurrence of floods and landslides. They found “the

frequency of extreme rainfall events in this area declined by more than 50% in the 1990s compared to the 1950s.” In addition, the “impact frequency also decreased, with landslide-event frequency changing from 1.6/year in the period 1955–1962 to 0.3/year from 1985 to 2005, while flood frequency peaked at 1.0/year in the late 1970s before declining to less than 0.2/year from 1990.” If the climate-driven changes that occurred over the latter part of the twentieth century continue, Clarke and Rendell conclude, “the landscape of southern Italy and the west-central Mediterranean will become increasingly stable.”

Conclusions

Several studies from the Mediterranean region show summer precipitation in the eastern Mediterranean became less variable as late twentieth century warming occurred than it had been in the earlier part of the century or in previous centuries. None of the Mediterranean studies provides evidence for the rising or more variable precipitation in the late twentieth century predicted by global climate models.

References

- Alexandrov, V., Schneider, M., Koleva, E., and Moisselin, J.-M. 2004. Climate variability and change in Bulgaria during the 20th century. *Theoretical and Applied Climatology* 79: 133–149.
- Clarke, M.L. and Rendell, H.M. 2006. Hindcasting extreme events: The occurrence and expression of damaging floods and landslides in southern Italy. *Land Degradation and Development* 17: 365–380.
- Crisci, A., Gozzini, B., Meneguzzo, F., Pagliara, S., and Maracchi, G. 2002. Extreme rainfall in a changing climate: regional analysis and hydrological implications in Tuscany. *Hydrological Processes* 16: 1261–1274.
- Grove, A.T. 2001. The “Little Ice Age” and its geomorphological consequences in Mediterranean Europe. *Climatic Change* 48: 121–136.
- Rodrigo, F.A., Esteban-Parra, M.J., Pozo-Vazquez, D., and Castro-Diez, Y. 2000. Rainfall variability in southern Spain on decadal to centennial time scales. *International Journal of Climatology* 20: 721–732.
- Rodrigo, F.S., Pozo-Vazquez, D., Esteban-Parra, M.J., and Castro-Diez, Y. 2001. A reconstruction of the winter North Atlantic Oscillation index back to A.D. 1501 using documentary data in southern Spain. *Journal of Geophysical Research* 106: 14,805–14,818.
- Sousa, A. and Garcia-Murillo, P. 2003. Changes in the wetlands of Andalusia (Doñana Natural Park, SW Spain) at

the end of the Little Ice Age. *Climatic Change* **58**: 193–217.

Tomozeiu, R., Lazzeri, M., and Cacciamani, C. 2002. Precipitation fluctuations during the winter season from 1960 to 1995 over Emilia-Romagna, Italy. *Theoretical and Applied Climatology* **72**: 221–229.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M.K., Erkan, N., Akkemik, U., and Stephan, J. 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics* **25**: 75–98.

6.1.1.4 Central Europe

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Central Europe include the following:

- Koning and Franses (2005) analyzed a century of daily precipitation data for the Netherlands, acquired at the de Bilt meteorological station in Utrecht. Using robust nonparametric techniques, they found the cumulative distribution function of annual maximum precipitation levels of rainfall remained constant throughout the period 1906–2002, leading them to conclude “precipitation levels are not getting higher.” The authors also report similar analyses performed for the Netherlands’ five other standard meteorological stations “did not find qualitatively different results.”
- Wilson *et al.* (2005) developed two March–August precipitation chronologies for the Bavarian Forest of southeast Germany, based on tree-ring widths obtained for the period 1456–2001. The first chronology, standardized with a fixed 80-year spline function (SPL), was designed to retain decadal and higher frequency variations; the second used regional curve standardization (RCS) to retain lower frequency variations. The SPL chronology failed to reveal any significant yearly or decadal variability, and there did not appear to be any trend toward either wetter or drier conditions over the 500-year period. The RCS reconstruction, by contrast, capturing lower frequency variation better, showed March–August precipitation was substantially greater than the long-term average during the periods 1730–1810 and 1870–2000 and less than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870. The found little evidence of a long-term trend, however, or of any relationship to accumulating CO₂ emissions.
- Solomina *et al.* (2005) derived the first spring

(April–July) tree-ring reconstruction for the period 1620–2002 for the Crimea Peninsula (Ukraine). This chronology was correlated with an earlier precipitation reconstruction derived from a sediment core taken in 1931 from nearby Saki Lake, providing a proxy precipitation record for the region that stretches back 1,500 years to AD 500. A parallel instrumental record from near the tree-sampling site shows no trend in precipitation over about the past century (1896–1988).

The reconstructed precipitation values from the tree-ring series revealed year-to-year and decadal variability but were near-average with relatively few extreme values between about the middle 1700s and the early 1800s, and again since about 1920. The most notable anomaly of the 1,500-year reconstruction was an “extremely wet” period between AD 1050 and 1250, which Solomina *et al.* describe as broadly coinciding with the Medieval Warm Period, when humidity was higher than during the instrumental era.

- Zanchettin *et al.* (2008) demonstrated rainfall variability across Europe is influenced by the interaction of NAO, ENSO, and the PDO. Multidecadal variability in these indices may produce nonstationary rainfall variability on multidecadal timescales.

Conclusions

These studies demonstrate enhanced precipitation did not occur in Central Europe during the twentieth century global warming.

References

- Koning, A.J. and Franses, P.H. 2005. Are precipitation levels getting higher? Statistical evidence for the Netherlands. *Journal of Climate* **18**: 4701–4714.
- Solomina, O., Davi, N., D’Arrigo, R., and Jacoby, G. 2005. Tree-ring reconstruction of Crimean drought and lake chronology correction. *Geophysical Research Letters* **32**: 10.1029/2005GL023335.
- Wilson, R.J., Luckman, B.H., and Esper, J. 2005. A 500 year dendroclimatic reconstruction of spring-summer precipitation from the lower Bavarian Forest region, Germany. *International Journal of Climatology* **25**: 611–630.
- Zanchettin, D., Franks, S.W., Traverso, P., and Tomasino, M. 2008. On ENSO impacts on European wintertime rainfalls and their modulation by the NAO and the Pacific multi-decadal variability. *International Journal of Climatology* **28**: 995–1006.

6.1.1.5. Boreal

Earlier Research

Earlier Boreal research concerning the relationship between precipitation and climate change include the following papers:

- Hanna *et al.* (2004) analyzed variations in several climatic variables in Iceland over the past century, including precipitation. For the period 1923–2002, precipitation appeared to have increased slightly, although they question the veracity of the trend citing several biases that may have corrupted the data base.
- Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June–August) precipitation in east central Sweden. This work revealed a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record. Over the past century of supposedly unprecedented global warming, however, precipitation was found to have exhibited less variability than it did during the preceding 150 years.
- Linderholm and Chen (2005) derived a 500-year winter (September–April) precipitation chronology using tree-ring data obtained from the forest zone of west-central Scandinavia. Their record exhibited considerable variability except for a fairly stable period of above-average precipitation between AD 1730 and 1790. Above-average winter precipitation also was found to have occurred in 1520–1561, 1626–1647, 1670–1695, 1732–1851, 1872–1892, and 1959 to the present, with the highest values reported in the early to mid-1500s. Below-average winter precipitation was observed during 1504–1520, 1562–1625, 1648–1669, 1696–1731, 1852–1871, and 1893–1958, with the lowest values occurring at the beginning of the record and the beginning of the seventeenth century.

Conclusions

These findings demonstrate conditions irregularly alternating between wetter and drier than the present have occurred repeatedly within the Boreal region throughout the past five centuries, with no particular sign of an additional influence from carbon dioxide emissions in the late twentieth century. Similar conditions can be expected to recur naturally in the future.

References

- Hanna, H., Jónsson, T., and Box, J.E. 2004. An analysis of Icelandic climate since the nineteenth century. *International Journal of Climatology* **24**: 1193–1210.
- Linderholm, H.W. and Chen, D. 2005. Central Scandinavian winter precipitation variability during the past five centuries reconstructed from *Pinus sylvestris* tree rings. *Boreas* **34**: 44–52.
- Linderholm, H.W. and Molin, T. 2005. Early nineteenth century drought in east central Sweden inferred from dendrochronological and historical archives. *Climate Research* **29**: 63–72.

6.1.1.6. Arctic

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Arctic region include the following:

- Curtis *et al.* (1998) examined a number of climatic variables at two first-order Arctic weather stations (Barrow and Barter Island, Alaska) from records that began in 1949. Both the frequency and mean intensity of precipitation decreased at these stations over the period of record. Though temperatures in the western Arctic increased over this period, “the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere.” The four researchers conclude the theoretical model-based assumption that “increased temperature leads to high precipitation ... is not valid,” at least for the part of the western Arctic that was the focus of their study.
- Lamoureux (2000) analyzed varved sediments from Nicolay Lake, Cornwall Island, Nunavut, Canada, comparing them with rainfall events recorded at a nearby weather station over the period 1948–1978. A rainfall history was established for the region over the 487-year period 1500–1987. The record was suggestive of a small, statistically insignificant increase in rainfall over the period. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic as well as the Arctic as a whole. Lamoureux also found “more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic

types during the coldest periods of the Little Ice Age.”

- Rawlins *et al.* (2006) calculated trends in the averaged water equivalent of annual rainfall and snowfall for 1936–1999 across the six largest Eurasian drainage basins that feed major rivers delivering water to the Arctic Ocean. The annual rainfall across the total area of the six basins decreased consistently and significantly over the 64-year period. Annual snowfall, by contrast, underwent a strongly significant increase until the late 1950s. Thereafter, snowfall declined, and “no significant change [was] determined in Eurasian-basin snowfall over the entire 64-year period.” Overall, annual total precipitation (rainfall and snowfall) decreased over the period of this study. The authors report their finding is “consistent with the reported (Berezovskaya *et al.*, 2004) decline in total precipitation.”

Conclusions

These studies, and especially that of Lamoureux (2000), show the late twentieth century warming was accompanied by a *reduction* in the number of weather extremes related to precipitation in a part of the planet predicted to be most affected by CO₂-induced global warming, the Canadian High Arctic.

Thus we can conclude either the theoretical arguments and model predictions that suggest “high-latitude precipitation increases in proportion to increases in mean hemispheric temperature” are not robust; or late twentieth century temperatures were not warmer than those of the mid-1930s and ‘40s; or both of the above. All three conclusions fail to provide support for a key claim of the *Arctic Climate Impact Assessment* (2005).

References

- Arctic Climate Impact Assessment. 2005. *Arctic Climate Impact Assessment—Special Report*. Cambridge University Press, New York, New York, USA.
- Berezovskaya, S., Yang, D., and Kane, D.L. 2004. Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds. *Geophysical Research Letters* **31**: 10.1029/2000GL021277.
- Curtis, J., Wendler, G., Stone, R., and Dutton, E. 1998. Precipitation decrease in the western Arctic, with special emphasis on Barrow and Barter Island, Alaska. *International Journal of Climatology* **18**: 1687–1707.
- Lamoureux, S. 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian

High Arctic recorded in lacustrine varves. *Water Resources Research* **36**: 309–318.

6.1.1.7. United States

For the most part, droughts in the United States have become shorter, less frequent, and less severe over the past century, and they have covered smaller areas (Figure 6.1.1.7.1).

Chen *et al.* (2012) set out to test the prediction that an increase in air temperature would result in higher evapotranspiration, thereby reducing available water and causing drought (IPCC, 2007; Karl *et al.*, 2009). Though the basis for the prediction is unsound, the test nonetheless revealed important results about the standard precipitation index (SPI) in relation to drought intensity for the Southern United States for 1895–2007. Chen *et al.* found “no obvious increases in drought duration and intensity during 1895–2007” and “no obvious increase in air temperature for the entire SUS during 1895–2007.”

Conclusions

Once again, predictions made by the IPCC (2007) and the authors of the U.S. climate report of 2009 (Karl *et*

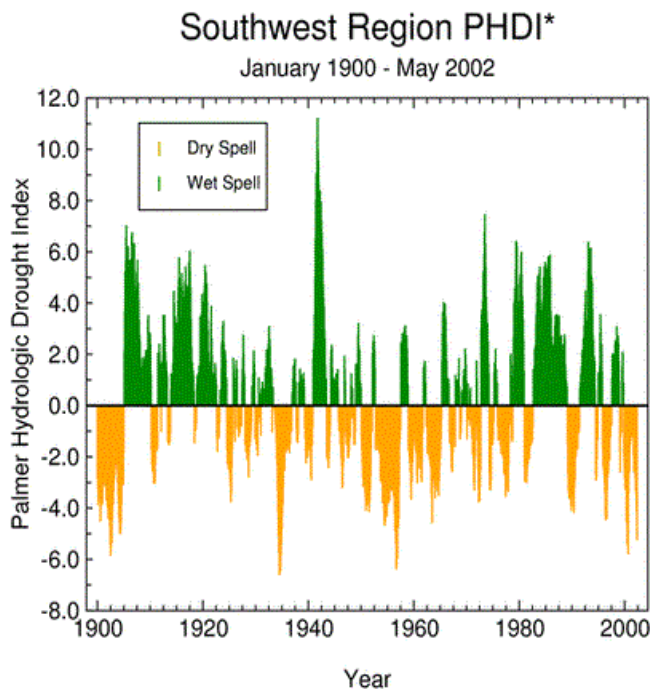


Figure 6.1.1.7.1. Drought Index for the southwestern US, 1900–2002. National Climatic Data Center, National Environmental Satellite, Data, and Information Service, National Oceanographic and Atmospheric Administration, <http://www.ncdc.noaa.gov/sotc/drought/2002/5#paleo>.

al., 2009), who warn of intensification of the hydrological cycle with increasing severity of extremes, are found to be without any confirmation in pertinent real-world data.

References

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., Chappelka, A.H., Prior, S.A., and Lockaby, G.B. 2012. Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. *Climatic Change* **114**: 379–397.

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Karl, T.R., Melillo, J.M., and Peterson, T.C. 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press, Cambridge, United Kingdom.

Earlier Research

Earlier U.S. hydrological studies with respect to global warming include the following papers.

- Haston and Michaelsen (1997) used proxy tree-ring data to develop a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border. Although regionwide precipitation during the twentieth century was higher than during the preceding three centuries, they found, it also was “less variable compared to other periods in the past.” However, Pierce *et al.* (2013) reviewed the results of 25 model projections of precipitation changes for California by 2060. They found 12 projected drier conditions and 13 projected wetter conditions, concluding California was likely to become drier, in contrast to the weak trend reported by Haston and Michaelsen.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. They detected a significant increasing trend in annual precipitation in the basin, driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range; at the same time, essentially no change occurred at the high-intensity end of the spectrum. For streamflow, no trend occurred at the annual timescale but monthly totals

increased in low-flow months and decreased in high-flow months. No correlation exists between those changes and the CO₂ content of the atmosphere.

- Cronin *et al.* (2000) analyzed salinity gradients in sediment cores from Chesapeake Bay, the largest estuary in the United States, to determine precipitation variability in the surrounding watershed over the past 1,000 years. The authors identified a high degree of decadal and multidecadal variability between wet and dry conditions throughout the record, with inferred regional precipitation fluctuating by between 25 and 30 percent, often in “extremely rapid [shifts] occurring over about a decade.” Precipitation over the past two centuries was on average greater than during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the climate was judged to have been “extremely wet.” The researchers also determined this region, like the southwestern United States, had experienced several “mega-droughts” lasting from 60 to 70 years, some being “more severe than twentieth century droughts.”
- Cowles *et al.* (2002) analyzed snow-water equivalent (SWE) data for 1910–1988 obtained at more than 2,000 sites in the western United States using four measuring systems—snow courses, snow telemetry, aerial markers, and airborne gamma radiation. Though the whole-area trend in SWE was negative, significant differences from trend occurred in the southern Rocky Mountains where no change occurred with time. Cowles *et al.* note their results “reinforce more tenuous conclusions made by previous authors,” citing Changnon *et al.* (1993) and McCabe and Legates (1995), who studied snowpack data from 1951–1985 and 1948–1987, respectively, at 275 and 311 sites. They too found a decreasing trend in SWE at most sites in the Pacific Northwest but more ambiguity in the southern Rockies.
- Garbrecht and Rossel (2002) used state divisional monthly precipitation data from the U.S. National Climatic Data Center to investigate precipitation on the Great Plains from January 1895 through December 1999. The authors found regions in the central and southern Great Plains experienced above-average precipitation over the past two decades of the twentieth century, and this 20-year period marked the longest and most intense wet interval of the 105 years of record. The enhanced precipitation resulted primarily from a reduction in the number of dry years and an increase in the number of wet years. The number of very wet years did not increase as much and showed a decrease for many regions. The northern and northwestern Great Plains also

experienced a precipitation increase at the end of this 105-year interval, but it was primarily confined to the final decade of the twentieth century and again was marked by the occurrence of fewer dry years, not increased wet ones.

- McCabe and Wolock (2002) evaluated precipitation trends for the conterminous United States for 1895–1999. They considered annual precipitation minus annual potential evapotranspiration (net precipitation), surplus water that eventually becomes streamflow, and any water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. For the United States as a whole, they found a statistically significant increase in the first two of these three parameters, while for the third there was no change.
- Kunkel *et al.* (2003) also studied the conterminous United States, using a new database of daily precipitation observations for the period 1895–2000. The new data indicated heavy precipitation occurred more commonly during the late nineteenth and early twentieth centuries, decreased to a minimum in the 1920s and 1930s, and then increased into the 1990s. Kunkel *et al.* note “for 1-day duration events, frequencies during 1895–1905 are comparable in magnitude to frequencies in the 1980s and 1990s” and “for 5- and 10-day duration events, frequencies during 1895–1905 are only slightly smaller than late 20th century values.”
- Ni *et al.* (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico using a network of 19 tree-ring chronologies. With respect to drought, they found “sustained dry periods comparable to the 1950s drought” occurred in “the late 1000s, the mid 1100s, 1570–97, 1664–70, the 1740s, the 1770s, and the late 1800s.” They also note the 1950s drought “was large in scale and severity, but it only lasted from approximately 1950 to 1956,” whereas the sixteenth century megadrought lasted more than four times as long. With respect to rainfall, Ni *et al.* report several wet periods comparable to the wet conditions seen in the early 1900s and after 1976 occurred in “1108–20, 1195–1204, 1330–45, the 1610s, and the early 1800s.” They also note “the most persistent and extreme wet interval occurred in the 1330s.”

Regarding the causes of the precipitation extremes, Ni *et al.* state “the 1950s drought corresponds to La Niña/-PDO [Pacific Decadal Oscillation] and the opposite polarity [+PDO] corresponds to the post-1976 wet period.” This led

them to hypothesize that the prominent shifts seen in the 1,000-year precipitation reconstructions from Arizona and New Mexico may be linked to strong shifts in the coupled ENSO-PDO system.

- Using collated paleo-data, Verdon and Franks (2006) demonstrated PDO phases are significantly associated with changes in the frequency of both warm and cold ENSO events. This multidecadal variability of event frequency has marked implications for secular trends in U.S. climate, as also discovered by Ni *et al.* (2002).
- Gray *et al.* (2003) examined 15 tree-ring-width series used in previous reconstructions of drought for evidence of low-frequency variation in precipitation in five regions of the central and southern Rocky Mountains. They identified strong multidecadal phasing of moisture variation in all regions, a late sixteenth century megadrought, and showed “oscillatory modes in the 30–70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought.” Like Ni *et al.* (2002), they note these changes “may ensue from coupling of the cold phase PDO [Pacific Decadal Oscillation] with the warm phase AMO [Atlantic Multidecadal Oscillation] (Cayan *et al.*, 1998; Barlow *et al.*, 2001; Enfield *et al.*, 2001),” something they envision happened in both the severe drought of the 1950s and the late sixteenth century megadrought.

Conclusions

Nearly all climate models suggest the planet’s hydrologic cycle will be enhanced in a warming world and that precipitation should therefore have increased in the late twentieth century. This prediction is especially applicable to the Pacific Northwest of the United States, where Kusnierczyk and Ettl (2002) report climate models predict “increasingly warm and wet winters,” as do Leung and Wigmosta (1999). As Cowles *et al.* (2002) show clearly, however, precipitation that fell and accumulated as snow in the western U.S. and Pacific Northwest during the late twentieth century was in fact reduced, not enhanced (see Figure 6.1.1.7.2).

Other studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, and El Niño-Southern Oscillation implicated as controlling factors.

Thus there appears to be nothing unusual about the extremes of wetness and dryness experienced

Observations: The Hydrosphere and Oceans

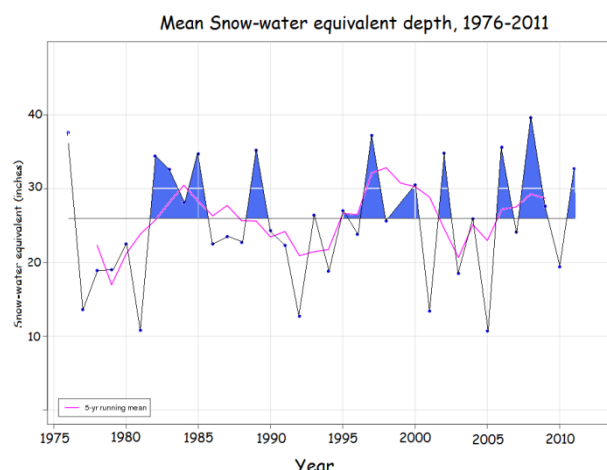


Figure 6.1.1.7.2. Mean snow accumulation in western USA, 1975-2011 (US National Resources Conservation Service, SNOTEL).

during the twentieth century that requires atmospheric CO₂ forcing to be invoked as a causative factor. In particular, several studies show frequencies of extreme precipitation events in the United States in the late 1800s and early 1900s were about as high as in the 1980s and 1990s. Natural variability in the frequency of precipitation extremes is large on decadal and multidecadal time scales and cannot be discounted as the cause or one of the causes of recent increases in precipitation where they have occurred.

Cronin *et al.*'s (2002) work, like the study of Ni *et al.* (2002), reveals nothing unusual about precipitation in the United States during the twentieth century, the last two decades of which the IPCC claims were the warmest of the past two millennia. Cronin *et al.*'s work indicates, for example, both wetter and drier intervals occurred repeatedly in the past in the Chesapeake Bay watershed. There is reason to believe such intervals will occur in the future with or without any further global warming.

Great concern has been expressed that increasing concentrations of carbon dioxide in the atmosphere will cause global warming that will in turn adversely affect water resources. The results of nearly all available U.S. studies reveal that during the twentieth century warming just the opposite has occurred: Moisture has become more available, and there has been no change in the amount of water required for optimum plant growth.

References

Barlow, M., Nigam, S., and Berberry, E.H. 2001. ENSO, Pacific decadal variability, and U.S. summertime

precipitation, drought and streamflow. *Journal of Climate* **14**: 2105–2128.

Cayan, D.R., Dettinger, M.D., Diaz, H.F., and Graham, N.E. 1998. Decadal variability of precipitation over western North America. *Journal of Climate* **11**: 3148–3166.

Changnon, D., McKee, T.B., and Doesken, N.J. 1993. Annual snowpack patterns across the Rockies: Long-term trends and associated 500-mb synoptic patterns. *Monthly Weather Review* **121**: 633–647.

Cowles, M.K., Zimmerman, D.L., Christ, A., and McGinnis, D.L. 2002. Combining snow water equivalent data from multiple sources to estimate spatio-temporal trends and compare measurement systems. *Journal of Agricultural, Biological, and Environmental Statistics* **7**: 536–557.

Cronin, T., Willard, D., Karlsen, A., Ishman, S., Verardo, S., McGeehin, J., Kerhin, R., Holmes, C., Colman, S., and Zimmerman, A. 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. *Geology* **28**: 3–6.

Enfield, D.B., Mestas-Núñez, A.M., and Trimble, P.J. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* **28**: 277–280.

Garbrecht, J.D. and Rossel, F.E. 2002. Decade-scale precipitation increase in Great Plains at end of 20th century. *Journal of Hydrologic Engineering* **7**: 64–75.

Gray, S.T., Betancourt, J.L., Fastie, C.L., and Jackson, S.T. 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. *Geophysical Research Letters* **30**: 10.1029/2002GL016154.

Haston, L. and Michaelsen, J. 1997. Spatial and temporal variability of southern California precipitation over the last 400 yr and relationships to atmospheric circulation patterns. *Journal of Climate* **10**: 1836–1852.

Kunkel, K.E., Easterling, D.R., Redmond, K., and Hubbard, K. 2003. Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophysical Research Letters* **30**: 10.1029/2003GL018052.

Kusnierczyk, E.R. and Ettl, G.J. 2002. Growth response of ponderosa pine (*Pinus ponderosa*) to climate in the eastern Cascade Mountain, Washington, U.S.A.: Implications for climatic change. *Ecoscience* **9**: 544–551.

Leung, L.R. and Wigmosta, M.S. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. *Journal of the American Water Resources Association* **35**: 1463–1471.

McCabe, A.J. and Legates, S.R. 1995. Relationships

between 700hPa height anomalies and 1 April snowpack accumulations in the western USA. *International Journal of Climatology* **14**: 517–530.

McCabe, G.J. and Wolock, D.M. 2002. Trends and temperature sensitivity of moisture conditions in the conterminous United States. *Climate Research* **20**: 19–29.

Molnar, P. and Ramirez, J.A. 2001. Recent trends in precipitation and streamflow in the Rio Puerco Basin. *Journal of Climate* **14**: 2317–2328.

Ni, F., Cavazos, T., Hughes, M.K., Comrie, A.C., and Funkhouser, G. 2002. Cool-season precipitation in the southwestern USA since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* **22**: 1645–1662.

Pierce, D.W., Cayan, D.R., Das, T., Maurer, E.P., Miller, N.L., Bao, Y., Kanamitsu, M., Yoshimura, K., Snyder, M.A., Guido, F., and Tyree, M. 2013. The Key Role of Heavy Precipitation Events in Climate Model Disagreements of Future Annual Precipitation Changes in California. *Journal of Climate* 10.1175/JCLI-D-12-00766.1.

Verdon, D.C. and Franks, S.W. 2006. Long-term behaviour of ENSO: Interactions with the PDO over the past 400 years inferred from paleoclimate records. *Geophysical Research Letters* **33**: doi: 10.1029/2005GL025052.

6.1.1.8. Canada and Mexico

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Canada and Mexico include the following:

- Lamoureux (2000) analyzed varved lake sediments from Nicolay Lake, Cornwall Island, Nunavut (Canada), comparing the resulting climate history with the 1948–1978 rainfall history recorded at a nearby weather station. This enabled the construction of a rainfall history for the 487-year period between 1500 and 1987. No statistically significant increase in total rainfall was found to have occurred over period studied. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic and the Arctic as a whole. In addition, Lamoureux states, “more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age.”
- Zhang *et al.* (2001) also studied the history of

heavy precipitation events across Canada, using “the most homogeneous long-term dataset currently available for Canadian daily precipitation.” No significant long-term trends were apparent in the data, and decadal-scale variability was the dominant feature of both the frequency and intensity of the annual extreme precipitation events. Seasonal data, however, revealed an increasing trend in the number of extreme autumn snowfall events and precipitation totals (extreme plus non-extreme events) revealed a slightly increasing trend due to increases in the number of non-heavy precipitation events. Zhang *et al.* concluded “increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada.”

- Diaz *et al.* (2002) created a 346-year history of winter-spring (November–April) precipitation for the Mexican state of Chihuahua, south of the U.S., using earlywood tree-ring width chronologies from more than 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua’s northeast border. Diaz *et al.* found “three of the five worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century.” Two of those three worst drought years occurred during a decadal period of average to slightly above-average precipitation, so the three years were not representative of long-term droughty conditions. The longest drought lasted 17 years (1948–1964), but for several of the years of that interval, precipitation values were only slightly below normal. Four very similar dry periods were interspersed throughout the preceding two-and-a-half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s. Considering the twentieth century alone, a long period of high winter-spring precipitation stretched from 1905 to 1932 and, following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record.

No long-term trend is apparent over the full 346 years of record, nor is there any evidence of a significant departure from no-trend over the twentieth century. Consequently, and despite the spasmodic drought events described above, Chihuahua’s precipitation history did not differ significantly during the twentieth century from what it was over the prior quarter of a millennium.

- The IPCC predicts global warming will produce

Observations: The Hydrosphere and Oceans

an increase in heavy precipitation. Kunkel (2003) looked for such a signal in precipitation data from Canada covering much of the last century but found “no discernible trend in the frequency of the most extreme [precipitation] events in Canada.”

Conclusions

Rainfall records from Canada and Mexico provide no support for the claim that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998). Neither a long-term trend nor a late twentieth century trend of increasing precipitation is apparent in most records, which are instead dominated mainly decadal variability.

References

Cubasch, U., Meehl, G.A., Boer, G.J., Stouffer, R.J., Dix, M., Noda, A., Senior, C.A., Raper, S., and Yap, K.S. 2001. Projections of future climate change. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A. (Eds.) *Climate Change 2001: The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.

Diaz, S.C., Therrell, M.D., Stahle, D.W., and Cleaveland, M.K. 2002. Chihuahua (Mexico) winter-spring precipitation reconstructed from tree-rings, 1647–1992. *Climate Research* **22**: 237–244.

Kharin, V.V. and Zwiers, F.W. 2000. Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *Journal of Climate* **13**: 3670–3688.

Kunkel, K.E. 2003. North American trends in extreme precipitation. *Natural Hazards* **29**: 291–305.

Lamoureux, S. 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. *Water Resources Research* **36**: 309–318.

Trenberth, K.E. 1998. Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change* **39**: 667–694.

Yonetani, T. and Gordon, H.B. 2001. Simulated changes in the frequency of extremes and regional features of seasonal/annual temperature and precipitation when atmospheric CO₂ is doubled. *Journal of Climate* **14**: 1765–1779.

Zhang, X., Hogg, W.D., and Mekis, E. 2001. Spatial and

temporal characteristics of heavy precipitation events over Canada. *Journal of Climate* **14**: 1923–1936.

Zwiers, F.W. and Kharin, V.V. 1998. Changes in the extremes of climate simulated by CCC GCM2 under CO₂-doubling. *Journal of Climate* **11**: 2200–2222.

6.1.2. Monsoons

Monsoonal climates bring abundant seasonal rainfall in Asia, northern Australia, South America, and South Africa. The Asian monsoon alone is said to influence nearly half of the world’s population, people whose agriculture, way of life, and society all depend on the regularity of the summer monsoon.

A particularly useful perspective on monsoonal variation in climatic context is provided by Vuille *et al.*’s (2012) study of the South American monsoon, which builds on earlier research by Bird *et al.* (2011). These authors use proxy records derived from speleothems, ice cores, and lake sediments from the tropical Andes and Southeast Brazil to reconstruct a history of the monsoon system over the past two thousand years. They report very coherent monsoonal behavior over the past two millennia, in which decadal to multidecadal variability is superimposed on large climatic excursions that occurred during the Medieval Warm Period, Little Ice Age, and late twentieth century warm period. Monsoonal strengthening occurred during the LIA and weakening during the two warm periods. Vuille *et al.* conclude the longer scale climate anomalies “were at least partially driven by temperature changes in the Northern Hemisphere and in particular over the North Atlantic, leading to a latitudinal displacement of the Intertropical Convergence Zone and a change in monsoon intensity (amount of rainfall upstream over the Amazon Basin).”

Li *et al.* (2012) also provide context for changes in monsoonal activity, developing a summer surface salinity reconstruction for the past millennium from the Southern Okinawa Trough, East China Sea, based on a high-resolution diatom record. They found high-salinity conditions generally prevailed during the Medieval Warm Period (905–1450 AD), whereas the Little Ice Age was characterized by relatively low-salinity conditions, perhaps caused by increased freshwater discharge from Taiwan’s Lanyang River.

The East Asian monsoon is a highly active and important part of the global climate system, with heavy summer monsoonal precipitation causing large discharges of freshwater into the southeastern East China Sea, variability in which has been documented from speleothem records (Wang *et al.*, 2001, 2008;

Partin *et al.*, 2007; Chang *et al.*, 2009). The report by Li *et al.* of increased China Sea region monsoonal activity during the Medieval Warm Period, and its reduction during the Little Ice Age, based on marine salinity variations, is an important confirmation of earlier land-based studies.

Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models, each with distinct physics and resolution, to simulate characteristics of the modern South American Monsoon System (SAMS). Model outputs were compared with data for the onset, end, and total rainfall of SAMS, as characterized by precipitation data for the period 1979–2006 derived from the Global Precipitation Climatology Project.

Bombardi and Carvalho found the annual precipitation cycle for SAMS “is poorly represented by most models”; for example, “poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models.” Most models, they note, “tend to underestimate precipitation during the peak of the rainy season.” The authors attribute the failure of the modeling to “the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle,” noting also, “simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon.”

In a similar study, Zhang *et al.* (2012) assessed the efficacy of GCM models to project variability and changes in the Asian monsoon. They used daily precipitable water and 850 hPa monsoon wind data to analyze potential changes in Asian monsoon onset, retreat, and duration, as simulated by 13 IPCC AR4 models. They report no model stands out as better than the 12 others and some models show “significant biases in mean onset/retreat dates and some failed to produce the broad features of how [the] monsoon evolves.” Flagrant contradictions occur between different groups of models. Over Asian land, for example, the 13 models “are nearly equally divided about the sign of potential changes of onset/retreat.” Zhang *et al.* concede they “do not know why the models are different in simulating these dominant processes and why in some models the ENSO influence is more significant than others.” They acknowledge also, as already found by Solomon *et al.* (2007) and Wang *et al.* (2009), that it is “unclear what are the key parameterizations leading to the differences in simulating ENSO and its responses to global warming.” In an important but little-cited statement, Zhang *et al.* conclude “there is a long way

ahead before we can make skillful and reliable prediction of monsoon onset, duration, intensity and evolution in [a] warmed climate.”

Kim *et al.* (2012) studied the Asian monsoon using retrospective predictions (1982–2009) from the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) seasonal prediction systems. Both the SYS4 and CFSv2 models exhibited a cold bias in sea-surface temperature (SST) compared with observations over the Equatorial Pacific, North Atlantic, Indian Oceans, and a broad region in the Southern Hemisphere and a warm bias over the northern part of the North Pacific and North Atlantic Oceans. Additionally, the models predict excessive precipitation along the Intertropical Convergence Zone, equatorial Atlantic, equatorial Indian Ocean, and the maritime continent. The researchers found the southwest monsoon flow and Somali Jet are stronger in SYS4, while the southeasterly trade winds over the tropical Indian Ocean, the Somali Jet, and the Subtropical northwestern Pacific high are weaker in CFSv2 relative to the reanalysis.

Wang *et al.* (2013) investigated the decadal variability of the Northern Hemisphere summer monsoon. They found the variability observed since the 1970s was associated with an intensification of Hadley and Walker circulation, contradicting theoretical predictions and numerical model projections. They propose an alternative index, the mega-El Niño/Southern Oscillation, which combined with the AMO provides a good predictor of monsoon intensity. Their analysis shows the importance of internal feedback processes and displays a poor correspondence with global warming, although Wang *et al.* suggest it is consistent with projections of a warm Northern Hemisphere-cold Southern Hemisphere due to greenhouse gas forcing, due to an increased thermal gradient between the hemispheres based on the ERA-40 and ERAI reanalysis datasets.

Conclusions

The reports by Vuill *et al.* (2012) and Li *et al.* (2012) show both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period. Moreover, Bombardi and Carvalho (2009), Zhang *et al.* (2012), and Kim *et al.* (2012) unanimously conclude the predictive skill of monsoon models is inadequate. If the climate modeling enterprise cannot simulate the monsoonal precipitation that affects almost half the world’s population, climate GCMs cannot be anywhere near good enough to be relied on as a basis for setting policy.

References

- Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Rosenmeier, M.F., and Stansell, N.D. 2011. A 2300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences USA* **108**: 8583–8588.
- Bombardi, R.J. and Carvalho, L.M.V. 2009. IPCC global coupled model simulations of the South America monsoon system. *Climate Dynamics* **33**: 893–916.
- Chang, Y.P., Chen, M.T., Yokoyama, Y., Matsuzaki, H., Thompson, W.G., Kao, S.J., and Kawahata, H. 2009. Monsoon hydrography and productivity changes in the East China Sea during the past 100,000 years: Okinawa Trough evidence (MD012404). *Paleoceanography* **24**: 10.1029/2007PA001577.
- Kim, H.-M., Webster, P.J., Curry, J.A., and Toma, V.E. 2012. Asian summer monsoon prediction in ECMWF System 4 and NCEP CFSv2 retrospective seasonal forecasts. *Climate Dynamics* **39**: 2975–2991.
- Li, D., Knudsen, M.F., Jiang, H., Olsen, J., Zhao, M., Li, T., Knudsen, K.L., Seidenkrantz, M.-S., and Sha, L. 2012. A diatom-based reconstruction of summer sea-surface salinity in the Southern Okinawa Trough, East China Sea, over the last millennium. *Journal of Quaternary Science* **27**: 771–779.
- Partin, J.W., Cobb, K.M., Adkins, J.F., Clark, B., and Fernandez, D.P. 2007. Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum. *Nature* **449**: 452–455.
- Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.) 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H., and Novello, V.F. 2012. A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past* **8**: 1309–1321.
- Wang, B., Liu, J., Kim, H.-Y., Webster, P.J., Yim, S.-Y., and Xiang, B. 2013. Northern Hemisphere Summer Monsoon Intensified by mega-El Niño/southern Oscillation and Atlantic Multidecadal Oscillation. *Proceedings of the National Academy of Sciences* **110** (14): 5347–5352. 10.1073/pnas.1219405110
- Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., and Dorale, J.A. 2001. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science* **294**: 2345–2348.
- Wang, Y.J., Cheng, H., Edwards, R.L., Kong, X.G., Shao, X.H., Chen, S.T., Wu, J.Y., Jiang, X.Y., Wang, X.F., and An, Z.S. 2008. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. *Nature* **451**: 1090–1093.
- Wang, X., Wang, D., and Zhou, W. 2009. Decadal variability of twentieth-century El Niño and La Niña occurrence from observations and IPCC AR4 coupled models. *Geophysical Research Letters* **36**: 10.1029/2009GL037929.
- Zhang, H., Liang, P., Moise, A., and Hanson, L. 2012. Diagnosing potential changes in Asian summer monsoon onset and duration in IPCC AR4 model simulations using moisture and wind indices. *Climate Dynamics* **39**: 2465–2486.

Earlier Research

Many other important papers have been published on the topic of the monsoon from the Middle East and across central Asia to Japan, including these:

- Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods for this record revealed “variations over the recent period of instrumental data are not unusual relative to the prior record.” Though more frequent extended wet periods have occurred in recent decades, this observation “does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models,” they write. Spectral analysis of the data reveals significant periodicities around 12 and 20–24 years, possibly “evidence for solar influences in these reconstructions for northeastern Mongolia.”
- Neff *et al.* (2001) considered a ^{14}C growth-ring record and a $\delta^{18}\text{O}$ proxy record of monsoon rainfall intensity from an early Holocene (9,600–6,100 yBP) speleothem from northern Oman. Correlation between the two datasets was “extremely strong” and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the $\delta^{18}\text{O}$ record, and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Because variations in ^{14}C are generally attributed to variations in solar activity and the ^{14}C record correlated strongly with the $\delta^{18}\text{O}$ record, and because their spectral analyses supported that correlation, Neff *et al.* conclude there is “solid evidence” that both signals stem from solar forcing.
- Kripalani *et al.* (2003) set out to test IPCC predictions of increased variability and strength of the

Asian monsoon under a global warming regime. The authors examined Indian monsoon rainfall for 1871–2001 using data obtained from 306 stations distributed across the country. The rainfall records display distinctive, three decade-long, alternating epochs of above- and below-normal rainfall but “no clear evidence to suggest that [either] the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming.”

- Similar conclusions have been reached by several other authors. For example, “Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances over the Bay of Bengal and the Arabian Sea using 100-year (1890–1999) data and found significant decreasing trends.” Kripalani *et al.* find “no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by [the] greenhouse warming scenario in model simulations.” They conclude “the analysis of observed data for the 131-year period (1871–2001) suggests no clear role of global warming in the variability of monsoon rainfall over India,” much as Kripalani and Kulkarni (2001) had concluded two years earlier.

- Kanae *et al.* (2004) examined the number and intensity of heavy precipitation events by comparing a climate-model-derived hypothesis with digitalized hourly precipitation data recorded at the Tokyo Observatory of the Japan Meteorological Agency for 1890–1999. The authors report many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s, making the 1990s seem to be unprecedented, but they note “hourly heavy precipitation around the 1940s is even stronger/more frequent than in the 1990s.” Their plots of maximum hourly precipitation and the number of extreme hourly precipitation events both rise fairly regularly from the 1890s to peak in the 1940s, after which declines set in that bottom out in the 1970s. The trend then reverses again, to rise to endpoints in the 1990s that are not yet as high as the peaks of the 1940s.

- Touchan *et al.* (2003) developed two reconstructions of spring (May–June) precipitation for southwestern Turkey from tree-ring width measurements for the periods 1776–1998 and 1339–1998. The reconstructions show clear evidence of multiyear to decadal variations in spring precipitation, but both dry and wet periods of 1–2 years were well distributed throughout the records. With respect to more extreme events, the period that preceded the

Industrial Revolution stood out, for “all of the wettest 5-year periods occurred prior to 1756” while the longest period of reconstructed spring drought was the four-year period 1476–1479, and the single driest spring was 1746. Turkey’s greatest precipitation extremes occurred well before the late twentieth century warm period.

- In a modeling study, Kim *et al.* (2012) assessed the seasonal predictive skill for the Asian monsoon for 1982–2009 by comparing retrodictions of the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) models with actual temperature and rainfall records. The models were found to perform poorly, exhibiting both regional warm (North Pacific and North Atlantic) and cold (Southern Hemisphere) temperature biases; excessive precipitation along the Intertropical Convergence Zone; and both stronger (SYS4 model) and weaker (CFSv2 model) projections of monsoon trade winds.

Conclusions

The evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. In some cases the data suggest the opposite, and overall they provide support for the proposition that precipitation responds mostly to cyclical variations in solar activity.

The results of Kim *et al.* (2012) demonstrate there is a long way to go before GCM models can be viewed as reliable monsoon management aids. In addition, the results of Wang *et al.* (2013) suggest a better understanding of the role of internal feedback processes as captured by the ENSO, PDO, AMO, and other indices would provide a better approach to forecasting monsoon behavior than focusing solely on external forcings.

References

- Kanae, S., Oki, T., and Kashida, A. 2004. Changes in hourly heavy precipitation at Tokyo from 1890 to 1999. *Journal of the Meteorological Society of Japan* **82**: 241–247.
- Kim, H.-M., Webster, P.J., Curry, J.A., and Toma, V.E. 2012. Asian summer monsoon prediction in ECMWF System 4 and NCEP CFSv2 retrospective seasonal forecasts. *Climate Dynamics* **39**: 2975–2991.
- Kripalani, R.H. and Kulkarni, A. 2001. Monsoon rainfall variations and teleconnections over south and east Asia. *International Journal of Climatology* **21**: 603–616.

Observations: The Hydrosphere and Oceans

Kripalani, R.H., Kulkarni, A., Sabade, S.S., and Khandekar, M.L. 2003. Indian monsoon variability in a global warming scenario. *Natural Hazards* **29**: 189–206.

Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A. 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411**: 290–293.

Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. *Journal of Climate* **14**: 872–881.

Singh, O.P. 2001. Long term trends in the frequency of monsoonal cyclonic disturbances over the north Indian ocean. *Mausam* **52**: 655–658.

Touchan, R., Garfin, G.M., Meko, D.M., Funkhouser, G., Erkan, N., Hughes, M.K., and Wallin, B.S. 2003. Preliminary reconstructions of spring precipitation in southwestern Turkey from tree-ring width. *International Journal of Climatology* **23**: 157–171.

Wang, B., Liu, J., Kim, H.-Y., Webster, P.J., Yim, S.-Y., and Xiang, B. 2013. Northern Hemisphere summer monsoon intensified by mega-El Niño/southern oscillation and Atlantic Multidecadal Oscillation. *Proceedings of the National Academy of Sciences* **110** (14): 5347–5352. 10.1073/pnas.1219405110.

6.1.3. Snowfall, Avalanches

On March 20, 2000, a British newspaper reported “Snowfalls are just a thing of the past” based on statements by a member of the Climatic Research Unit of the University of East Anglia, who claimed within a few years snowfall will become “a very rare and exciting event” and “children just aren’t going to know what snow is.” The U.K.’s Hadley Centre for Climate Prediction and Research said eventually British children would have only a “virtual” experience of snow via movies and the Internet.

A model developed at the U.S. National Oceanic and Atmospheric Administration (NOAA) published in the *Journal of Climate* projected the majority of the planet would experience less snowfall as a result of global warming due to increasing atmospheric CO₂. The predicted decline in snowfall was expected to cause serious problems for ski resorts and areas in the western United States that rely on snowmelt as a source of fresh water. Oregon and Washington would get less than half their usual amount of snow.

In June 2013, more than 100 ski resorts, concerned global warming would reduce snowfall and curtail skiing, joined the Business for Innovative Climate and Energy Policy Climate Declaration

urging Americans to “use less electricity,” “drive a more efficient car,” and choose “clean energy” to combat climate change and save their ski resorts. The 2007 report of the IPCC warns of a difficult future for the industry: “...snow cover area is projected to contract[,] ... mountainous areas will face glacier retreat, reduced snow cover and winter tourism[, and] ... shifting of ski slopes to higher altitudes.”

And yet, three of the top five snowiest winters in the Northern Hemisphere on record have occurred in the past five years (Figure 6.1.3.1).

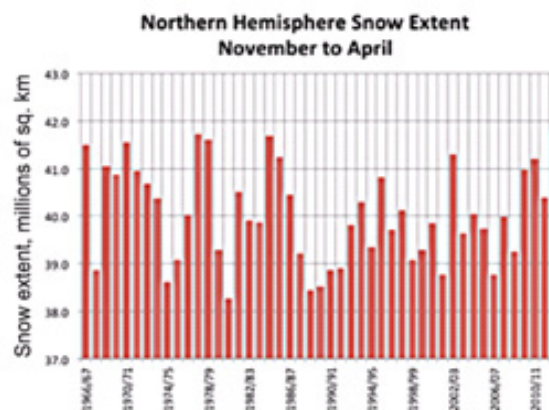


Figure 6.1.3.1. Annual winter snow extent in the Northern Hemisphere, November to April, 1966–2013 (Rutgers University, Global Snow Lab).

In related research, Eckert *et al.* (2010) examined the hypothesis that global warming might cause a dangerous increase in numbers of snow avalanches in the French Alps. Because avalanches are mainly governed by temperature fluctuations in combination with heavy snow and strong wind regimes, both Eckert *et al.* and the IPCC have deemed it likely they will be strongly influenced by climatic fluctuations. Eckert *et al.* analyzed snow avalanches using data from the *Enquete Permanente sur les Avalanches*—EPA, a chronicle that describes avalanche events on approximately 5,000 determined paths in the French Alps and the Pyrenees.

Eckert *et al.* found no strong changes in mean avalanche activity or in the number of winters of low or high activity over the last 60 years of record. Similar results have been reported from the Swiss Alps for the second half of the twentieth century by Latarnser and Schneebeli (2002) and by other researchers, including Schneebeli *et al.* (1997) and Bader and Kunz (2000), who report no change in extreme snowfalls and catastrophic avalanches around

Davos, Switzerland during the twentieth century. Jomelli *et al.* (2007) found “no correlation between the fluctuations in avalanche activity between 1978 and 2003 and large-scale atmospheric patterns” in the Maurienne Valley in France, and Jomelli and Pech (2004) suggest avalanche magnitude at low altitudes has declined since 1650 in the Massif des Ecrins in the French Alps.

References

Bader, S. and Kunz, P. 2000. *Climate Risks—The Challenge for Alpine Region—PNR31*. Verlag der Fachvereine Hochschulverlag AG an der ETH Zurich.

Eckert, N., Parent, E., Kies, R., and Baya, H. 2010. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: application to 60 years of data in the northern French Alps. *Climatic Change* **101**: 515–553.

Jomelli, V. and Pech, P. 2004. Effects of the little ice age on avalanche boulder tongues in the French Alps (Massif des Ecrins). *Earth Surface Processes and Landforms* **29**: 553–564.

Jomelli, V., Delval, C., Grancher, D., Escande, S., Brunstein, D., Hetu, B., Filion, L., and Pech, P. 2007. Probabilistic analysis of recent snow avalanche activity and climate in the French Alps. *Cold Regions Science and Technology* **47**: 180–192.

Laternser, M. and Schneebeli, M. 2002. Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. *Natural Hazards* **27**: 201–230.

Schneebeli, M., Laternser, M., and Ammann, W. 1997. Destructive snow avalanches and climate change in the Swiss Alps. *Eclogae Geologicae Helvetiae* **90**: 457–461.

Earlier Research

Other recent studies of the relationship between global warming and snow or avalanche activity include the following:

- Kunkel *et al.* (2009a and 2009b) used 440 long-term, homogeneous snowfall records to examine “temporal variability in the occurrence of the most extreme snowfall years, both those with abundant snowfall amounts and those lacking snowfall,” defined as the highest and lowest tenth percentile winter snow amounts. Their data came from the conterminous United States over the 107-year period from 1900–1901 to 2006–2007.

Kunkel *et al.* (2009b) found large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States,

balanced by large increases in the frequency of low-extreme snowfall years in the northeast, southeast, and northwest. The scientists determined overall “the area-weighted conterminous United States results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-year period.”

- Kilpelainen *et al.* (2010) report on the degree to which Finnish forests are damaged by snow load on their branches, claiming across Europe such loading “has accounted for a mean annual amount of almost one million cubic meters of damaged wood in managed forests over the period 1950–2000.” Damage results primarily from stem breakage or bending when the soil is frozen, although trees also can be uprooted if the soil is not frozen, and damage by insects or fungal attacks are common in trees suffering from snow damage.

To calculate risk of snow-induced damage, Kilpelainen *et al.* employed a snow accumulation model in which cumulative precipitation, air temperature, and wind speed were derived from the A2 scenario of the FINADAPT project (Ruosteenoja *et al.*, 2005), where the air’s CO₂ concentration was estimated to rise to 840 ppm by 2100 and mean air temperatures were projected to increase by almost 4°C in summer and more than 6°C in winter. The model was tested and trained using real-world data obtained by the Finnish Meteorological Institute (Venalainen *et al.*, 2005) for the 30-year baseline period of 1961–1990.

Defining the risk of snow-induced forest damage as proportional to the number of days per year when the accumulated amount of snow exceeds 20 kg m⁻², the six scientists calculated the mean annual number of risk days in Finland declined by 11 percent, 23 percent, and 56 percent relative to the 1961–1990 baseline period for the first, second, and third 30-day simulation periods they modeled (1991–2020, 2021–2050, and 2070–2099), respectively. For the most hazardous areas of northwest and northeast Finland they also report “the number of risk days decreased from the baseline period of over 30 days to about 8 days per year at the end of the century.”

- Peng *et al.* (2010) used snow-depth measurements collected at 279 meteorological stations in northern China, plus colocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate changes in snow depth for 1980–2006 and to analyze the effects of those changes on vegetative growth during the following spring and summer. Peng *et al.* report winter snow depth overall increased in northern China over the

past 30 years, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed. Here, positive correlations exist between mean winter snow depth and spring NDVI data. In addition, they note Piao *et al.* (2005) had determined the net primary productivity of the same desert and grasslands during 1982–1999 “increased by 1.6% per year and 1.1% per year, respectively” and “desertification has been reversed in some areas of western China since the 1980s,” as reported by Runnstrom (2000), Wu (2001), Zhang *et al.* (2003), and Piao *et al.* (2005). Peng *et al.* conclude the “increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms.” They further note the frequency of sand-dust storms has “declined in China since the early 1980s (Qian *et al.*, 2002; Zhao *et al.*, 2004).”

- Teich *et al.* (2012) analyzed 21 snow and weather variables associated with 189 winter forest avalanches in the Swiss Alps between 1985 and 2006, an acknowledged human hazard (Bebi *et al.*, 2009; Martin *et al.*, 2001). The avalanches were spread geographically throughout the Alps and at heights ranging from 700 to 2,200 m height. The researchers found the number of potential forest avalanche days decreased at 11 of 14 snow and weather stations [79 percent] for new snow forest avalanches and at 12 of 14 stations [86 percent] for old snow forest avalanches, independent of elevation and climatic region. They conclude such “negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under current climate change.” Thus, noting the currently observed increase in forest cover density in the Swiss Alps (Bebi *et al.*, 2001; Brandi, 2010; Krumm *et al.*, 2011), “it is likely that avalanche releases in forested terrain will become less frequent in the future.”

Conclusions

The cited studies indicate a warming generally does not affect the frequency of avalanches. For instance, and after a comprehensive review of the work of other scientists, Eckert *et al.* (2010) conclude “climate change has recently had little impact on the avalanching rhythm in this region [the French Alps].” Regarding forest damage, the decline in the number of risk days reported from northern Finland by Kilpelainen *et al.* (2010) represents a warming-induced decrease in risk of snow damage to forests on the order of 75 percent.

Peng *et al.*’s (2010) studies show as the world has warmed over the past three decades, China above 40°N latitude has seen an increase in winter snow depth that has promoted increased vegetative growth in desert areas and grasslands and resulted in a reduction in sand-dust storms. These climate-related changes are obviously positive developments.

References

- Bebi, P., Kienast, F., and Schonenberger, W. 2001. Assessing structures in mountain forests as a basis for investigating the forests’ dynamics and protective function. *Forest Ecology and Management* **145**: 3–14.
- Bebi, P., Kulakowski, D., and Rixen, C. 2009. Snow avalanche disturbances in forest ecosystems—state of research and implications for management. *Forest Ecology and Management* **257**: 1883–1892.
- Brandi, U.-B. 2010. Schweizerisches Landesforstinventar. Ergebnisse der dritten Erhebung 2004–2006. Birmensdorf: Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft. Bundesamt für Umwelt, Wald und Landschaft, Bern, Switzerland.
- Eckert, N., Parent, E., Kies, R., and Baya, H. 2010. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: application to 60 years of data in the northern French Alps. *Climatic Change* **101**: 515–553.
- Kilpelainen, A., Gregow, H., Strandman, H., Kellomäki, S., Venäläinen, A., and Peltola, H. 2010. Impacts of climate change on the risk of snow-induced forest damage in Finland. *Climatic Change* **99**: 193–209.
- Krumm, F., Kulakowski, D., Spiecker, H., Duc, P., and Bebi, P. 2011. Stand development of Norway spruce dominated subalpine forests of the Swiss Alps. *Forest Ecology and Management* **262**: 620–628.
- Kunkel, K.E., Palecki, M.A., Ensor, L., Easterling, D., Hubbard, K.G., Robinson, D., and Redmond, K. 2009a. Trends in twentieth-century U.S. extreme snowfall seasons. *Journal of Climate* **22**: 6204–6216.
- Kunkel, K.E., Palecki, M.A., Ensor, L., Hubbard, K.G., Robinson, D.A., Redmond, K.T., and Easterling, D.R. 2009b. Trends in twentieth-century U.S. snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology* **26**: 33–44.
- Martin, E., Giraud, G., Lejeune, Y., and Boudart, G. 2001. Impact of a climate change on avalanche hazard. *Annals of Glaciology* **32**: 163–167.
- Peng, S., Piao, S., Ciais, P., Fang, J., and Wang, X. 2010. Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology* **16**: 3004–3013.

Piao, S.L., Fang, J.Y., Liu, H.Y., and Zhu, B. 2005. NDVI-indicated decline in desertification in China in the past two decades. *Geophysical Research Letters* **32**: 10.1029/2004GL021764.

Qian, Z.A., Song, M.H., and Li, W.Y. 2002. Analysis on distributive variation and forecast of sand-dust storms in recent 50 years in north China. *Journal of Desert Research* **22**: 106–111.

Runnstrom, M.C. 2000. Is northern China winning the battle against desertification? Satellite remote sensing as a tool to study biomass trends on the Ordos plateau in semiarid China. *Ambio* **29**: 468–476.

Ruosteenoja, K., Jylha, K., and Tuomenvirta, H. 2005. Climate scenarios for FINADAPT studies of climate change adaptation. FINADAPT Working Paper 15. Helsinki, Finland: Finnish Environment Institute Mimeographs 345.

Teich, M., Marty, C., Gollut, C., Gret-Regamey, A., and Bebi, P. 2012. Snow and weather conditions associated with avalanche releases in forests: rare situations with decreasing trends during the last 41 years. *Cold Regions Science and Technology* 83-84: 77–88.

Venalainen, A., Tuomenvirta, H., and Pirinen, P. *et al.* 2005. A basic Finnish climate data set 1961–2000—description and illustrations. *Finnish Meteorological Institute Reports* 2005:5, Helsinki, Finland.

Wu, W. 2001. Study on process of desertification in Mu Us sandy land for last 50 years, China. *Journal of Desert Research* **21**: 164–169.

Zhang, L., Yue, L.P., and Xia, B. 2003. The study of land desertification in transitional zones between the UM US desert and the Loess plateau using RS and GIS—a case study of the Yulin region. *Environmental Geology* **44**: 530–534.

Zhao, C.S., Dabu, X., and Li, Y. 2004. Relationship between climatic factors and dust storm frequency in inner Mongolia of China. *Geophysical Research Letters* **31**: 10.1029/2003GL018351.

6.1.4. Evaporation

Evaporation is the primary source of atmospheric water vapor, a powerful greenhouse gas, and so is of particular interest to climate scientists. Huntington (2006) notes direct measurements of evaporation (pan evaporation) show a reduction in evaporation over the twentieth century, whereas indirect estimates suggest an increase.

Roderick and Farquhar (2002) linked a reduction in pan evaporation rates to a reduction in insolation (solar dimming) at ground level due to increasing cloud cover and atmospheric aerosols. Subsequently

Roderick *et al.* (2009a) calculated a reduction of 4.8 W/m² for Australia as driving the observed reduction in pan evaporation. The Australian results are extended to the global behavior by Roderick *et al.* (2009b), where a global reduction in pan evaporation is attributed to a combination of wind stilling and solar dimming. The authors also observe the interpretation of pan evaporation depends on whether the observations are from water-limited or energy-limited sites. For energy-limited sites, the evaporation occurs at the maximum rate possible for the radiative flux present, and declining pan evaporation also indicates declining evapo-transpiration. For water-limited sites, evaporation is restricted by the available water, and evapo-transpiration depends on the supply of precipitation. Therefore, Roderick *et al.* argue evapo-transpiration can rise while pan evaporation decreases, if the supply of precipitation increases sufficiently. This implies dry areas are getting wetter.

Recognizing the importance of near-surface wind speed for evaporation, McVicar *et al.* (2010) noted the “occurrence of widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years,” citing papers by Roderick *et al.* (2007), McVicar *et al.* (2007; 2008), Pryor *et al.* (2009), and Jiang *et al.* (2010). Such a change, now widely termed “stilling,” will be a key factor in reducing the atmospheric demand that drives actual evapotranspiration when water availability is not limited, as in the case of lakes and rivers.

In addition, McVicar *et al.* note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases (as demonstrated by McVicar *et al.*, 2007). Increasing wind speeds, they point out, lead to increases in atmospheric evaporative demand, and decreasing wind speeds do the opposite. These changes are significant for people who depend on water resources derived from mountainous headwater catchments: More than half the world’s population lives in catchments with rivers originating in mountainous regions (Beniston, 2005), and this water supports about 25 percent of the global gross domestic product (Barnett *et al.*, 2005).

Defining u_z as change in wind speed with change in elevation—that is, $u_z = \Delta u / \Delta z$, where $\Delta u = u_2 - u_1$, $\Delta z = z_2 - z_1$, and $z_2 > z_1$ —McVicar *et al.* calculated monthly averages of u_z , using 1960–2010 monthly average u data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China, and by MeteoSwiss at 37 sites in Switzerland. They suggest their research constitutes “the first time that long-term trends in u_z

in mountainous regions have been calculated,” and their u_z trend results show u to have declined more rapidly at higher than at lower elevations in both study areas.

The double benefit of a decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations should act to reduce water loss via evaporation from high-altitude catchments in many of the world’s mountainous regions, thus providing more water for people who obtain it from those sources. As McVicar *et al.* note, the “reductions in wind speed will serve to reduce rates of actual evapo-transpiration partially compensating for increases in actual evapo-transpiration due to increasing air temperatures.”

Some papers in the literature (e.g., Cai *et al.*, 2009), and also the published IPCC fourth and draft fifth *Assessment Reports*, confuse the causal physics of the relationship between temperature and evapotranspiration by assuming increasing temperature causes drought. In reality, when incoming radiation falls on a moist surface this energy is partitioned into evapotranspiration (latent heat) and heating of the near surface/atmosphere (sensible heat). During drought, where moisture is limited, less of the incoming energy can be used for latent heat (i.e., reduced evapotranspiration) and consequently more sensible heat occurs. The consequence is that air temperatures rise as evapotranspiration is reduced (Lockart *et al.*, 2009a, b).

References

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**: 303–309.

Beniston, M. 2005. Mountain climates and climatic change: An overview of processes focusing on the European Alps. *Pure and Applied Geophysics* **162**: 1587–1606.

Cai, W., Cowan, T., Briggs, P., and Raupach, M. 2009. Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia. *Geophysical Research Letters* **36**: L21709.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* **319**: 83–95.

Jiang, Y., Luo, Y., Zhao, Z., and Tao, S. 2010. Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology* **99**: 421–430.

Lockart, N., Kavetski, D., and Franks, S.W. 2009a. On the recent warming in the Murray-Darling Basin: land surface interactions misunderstood. *Geophysical Research Letters* **36**: L24405.

Lockart, N., Kavetski, D., and Franks, S.W. 2009b. On the role of soil moisture in daytime evolution of temperatures. *Hydrological Processes*, doi: 10.1002/hyp.9525

McVicar, T.R., Van Niel, T.G., Li, L.T., Hutchinson, M.F., Mu, X.-M., and Liu, Z.-H. 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology* **338**: 196–220.

McVicar, T.R., Van Niel, T.G., Li, L.T., Roderick, M.L., Rayner, D.P., Ricciardulli, L., and Donohue, R.G. 2008. Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters* **35**: 10.1029/2008GL035627.

McVicar, T.R., Van Niel, T.G., Roderick, M.L., Li, L.T., Mo, X.G., Zimmermann, N.E., and Schmatz, D.R. 2010. Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960–2006. *Geophysical Research Letters* **37**: 10.1029/2009GL042255.

Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski Jr., W.J., Nunes, A., and Roads, J. 2009. Wind speed trends over the contiguous United States. *Journal of Geophysical Research* **114**: 10.1029/2008JD011416.

Roderick, M.L. and Farquhar, G.D. 2002. The cause of decreased pan evaporation over the past 50 years. *Science* **298** (5597): 1410–1411, 10.1126/science.1075390-a.

Roderick, M.L., Hobbins, M.T., and Farquhar, G.D. 2009a. Pan evaporation trends and the terrestrial water balance. I. Principles and Observations. *Geography Compass* **3/2** (2009): 746–760, 10.1111/j.1749-8198.2008.00213.x.

Roderick, M.L., Hobbins, M.T., and Farquhar, G.D. 2009b. Pan evaporation trends and the terrestrial water balance. II. Energy Balance and Interpretation. *Geography Compass* **3/2** (2009): 761–780, 10.1111/j.1749-8198.2008.00214.x

Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., and Hobbins, M.T. 2007. On the attribution of changing pan evaporation. *Geophysical Research Letters* **34**: 10.1029/2007GL031166.

6.1.5. Drought

Even a moderate drought can have devastating effects on regional agriculture, water resources, and the environment. Many climate scientists and agriculturists have expressed growing concern about worldwide drying of land areas and increasing evapo-transpiration, which they attribute to man-induced

global warming. Some recent peer-reviewed studies suggest the severity and length of droughts is increasing over various regions due to global warming (e.g., Briffa *et al.*, 2009; Cai *et al.*, 2009). But in the United States, droughts have become shorter, less frequent, less severe, and less widespread over the past century, peaking during the Dust Bowl era of the 1930s, as clearly evidenced by the heat wave index for the period 1895–2008 (Figure 6.1.5.1).

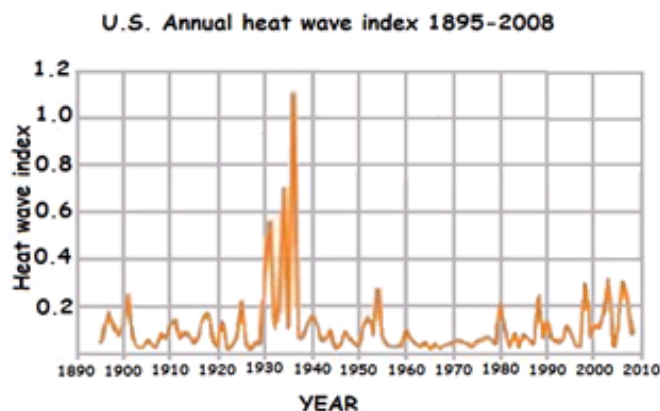


Figure 6.1.5.1. Heat Wave Index for USA, 1895–2008 (NOAA CCSP U.S. Climate Change Science Program, 2009).

Drought represents moisture deficit and therefore is an end-member of the precipitation spectrum. Many of the papers discussed earlier have referred to the issue. We include here several other important papers for which drought is the primary focus.

- Providing a long-term perspective of the climate cycle that stretches from the Medieval Warm Period to the late twentieth century warming, Laird *et al.* (2012) developed diatom-based proxy records for sediment cores from six lakes that provide a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada. The study was intended to address concerns that droughts similar to, or more extreme than, the 1930s Dust Bowl drought are a likely outcome of human-forced global warming and could perhaps last for several decades to centuries (Seager *et al.*, 2007; Cook *et al.*, 2010; Romm, 2011). A consequence of such droughts is decreased lake levels and river flows (Schindler and Lee, 2010).

Laird *et al.* reported a synchronous change had occurred across all of the six lakes, indicating “a period of prolonged aridity” during the Medieval Warm Period (c. 900–1400 AD). The general

coincidence in time of this event at the six sites suggests an extrinsic climate forcing (Williams *et al.*, 2011) of natural origin. A parallel study by Schmieder *et al.* (2011) of five topographically closed lakes in Nebraska “indicated relative (climate) coherency over the last 4000 years, particularly during the MCA [Medieval Climate Anomaly] with all lakes indicating lake-level decline.” Schmieder *et al.* also report “in Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al.*, 2008), high eolian deposition occurred from ~1280 to 1410 AD in Elk Lake (Dean, 1997) and $\delta^{18}\text{O}$ from calcite indicated an arid period from ~1100 to 1400 AD in Steel Lake (Tian *et al.*, 2006).” They note, “in Manitoba, the cellulose $\delta^{18}\text{O}$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 AD, and a less-severe dry period from 1320 to 1340 AD (Buhay *et al.*, 2009)” and relatively warm conditions during the Medieval Warm Period “have been inferred from pollen records in the central boreal region of Canada and in Wisconsin” (Viau and Gajewski, 2009; Viau *et al.*, 2012; Wahl *et al.*, 2012).”

- In a study of drought in the global context over the past 60 years, Sheffield *et al.* (2012) utilize datasets on temperature, precipitation, and surface energy parameters (wind, specific humidity, etc.) to calculate the standard Palmer Drought Severity Index (PDSI) using two different equations. The PDSI-TH (Thornwaite formulation of evapotranspiration) and PDSI-PM (Penman-Montheith formulation) differ in that the TH model estimates evapotranspiration on the basis of air temperature (a proxy for potential evapotranspiration, not because of causal physics), whereas PM offers a more physically based evapotranspiration formulation, where temperature is utilized only to calculate near surface atmosphere humidity deficit. The TH model implicitly assumes no trend in air temperatures over the long term. The PDSI-TH approach overestimates evapotranspiration as long-term trends in temperature are apparent. The PDSI-PM equation does not respond to the temperature trend, as temperature is only an indirect variable.

Both the older, conventional index (PDSI-TH) and the newer index (PDSI-PM) show an increase in drought over recent years, though the trend for the latter was not statistically significant. The regions of decreasing trends in potential evaporation are in general agreement with areas of global dimming, decreasing wind speed, and changes in other surface parameters but not temperature. These results suggest previous calculations of global drought have been

Observations: The Hydrosphere and Oceans

overestimated, and the authors conclude their study has implications for understanding changes in the terrestrial hydrological cycle and the future impacts of global warming on agriculture and water resources. Sheffield *et al.* (2009) arrived at similar conclusions.

Conclusions

The relationship between the occurrence of drought and global warming is, at best, weak. Nonetheless, in some places, such as North America, severe droughts occurred during the Medieval Warm Period. Given the absence of similar droughts during the warming in the late twentieth century, two conclusions follow. First, the Medieval Warm Period must have been more extreme in terms of both high temperature and its duration than anything experienced recently. Second, the occurrence of such extra warming is strong evidence that warmings greater than the recent one can occur without any help from rising atmospheric CO₂ concentrations, which were more than 100 ppm less during the Medieval Warm Period than they are today. This research thus suggests both recent warming and drought are the result of something other than anthropogenic CO₂ emissions.

References

Briffa, K.R., van der Schrier, G., and Jones, P.D. 2009. Wet and dry summers in Europe since 1750: evidence of increasing drought. *International Journal of Climatology* **29**: 1894–1905.

Buhay, W.M., Simpson, S., Thorleifson, H., Lewis, M., King, J., Telka, A., Wilkinson, P., Babb, J., Timsic, S., and Bailey, D. 2009. A 1000 year record of dry conditions in the eastern Canadian prairies reconstructed from oxygen and carbon isotope measurements on Lake Winnipeg sediment organics. *Journal of Quaternary Science* **24**: 426–436.

Cai, W., Cowan, T., Briggs, P., and Raupach, M. 2009. Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia. *Geophysical Research Letters* **36**: L21709.

Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2010. Mega-droughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* **25**: 48–61.

Dean, W.E. 1997. Rates, timing and cyclicity of Holocene eolian activity in north-central US: evidence from varved lake sediments. *Geology* **25**: 331–334.

Laird, K.R., Haig, H.A., Ma, S., Kingsbury, M.V., Brown, T.A., Lewis, C.F.M., Oglesby, R.J., and Cumming, B.F.

2012. Expanded spatial extent of the Medieval Climate Anomaly revealed in lake-sediment records across the boreal region in northwest Ontario. *Global Change Biology* **18**: 2869–2881.

Romm, J. 2011. The next dust bowl. *Nature* **478**: 450–451.

Schindler, D.W. and Lee, P.G. 2010. Comprehensive conservation planning to protect biodiversity and ecosystem services in Canadian boreal regions under a warming climate and increasing exploitation. *Biological Conservation* **143**: 1571–1586.

Schmieder, J., Fritz, S.C., Swinehart, J.B., Shinneman, A., Wolfe, A.P., Miller, G., Daniels, N., Jacobs, K., and Grimm, E.C. 2011. A regional-scale climate reconstruction of the last 4000 years from lakes in the Nebraska sand hills, USA. *Quaternary Science Reviews* **30**: 1797–1812.

Seager, R., Graham, N., Herweijer, C., Gorodn, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.

Sheffield, J., Andreadis, K.M., Wood, E.F., and Lettenmaier, D.P. 2009. Global and continental drought in the second half of the twentieth century: severity-area-duration analysis and temporal variability of large-scale events. *Journal of Climate* **22**: 1962–1981.

Sheffield, J., Wood, E.F., and Roderick, M.L. 2012. Little change in global drought over the past 60 years. *Nature* **491**: 435–438.

St. Jacques, J.M., Cumming, B.F., and Smol, J.P. 2008. A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west-central Minnesota, USA. *Quaternary Science Reviews* **27**: 781–796.

Tian, J., Nelson, D.M., and Hu, F.S. 2006. Possible linkages of late-Holocene drought in the North American midcontinent to Pacific Decadal Oscillation and solar activity. *Geophysical Research Letters* **33**: 10.1029/2006GL028169.

Viau, A.E. and Gajewski, K. 2009. Reconstructing millennial-scale, regional paleoclimates of boreal Canada during the Holocene. *Journal of Climate* **22**: 316–330.

Viau, A.E., Ladd, M., and Gajewski, K. 2012. The climate of North America during the past 2000 years reconstructed from pollen data. *Global and Planetary Change* **84–85**: 75–83.

Wahl, E.R., Diaz, H.F., and Ohlwein, C. 2012. A pollen-based reconstruction of summer temperature in central North America and implications for circulation patterns during medieval times. *Global and Planetary Change* **84–85**: 66–74.

Williams, J.W., Blois, J.L., and Shuman, B.N. 2011. Extrinsic and intrinsic forcing of abrupt ecological change:

case studies from the late Quaternary. *Journal of Ecology* **99**: 664677.

6.1.6. Rivers and Streamflow

Model projections suggest CO₂-induced global warming may induce large changes in global streamflow characteristics, which has led many authors and the IPCC to claim warming will lead to the intensification of the hydrological cycle and the occurrence of more floods (Labat, 2004; Huntington, 2006; Gerten *et al.*, 2008; Dai *et al.*, 2009).

Accordingly, many scientists have examined streamflow, or proxy streamflow, records in an effort to elucidate these claimed relationships. On the assumption that global runoff represents an integrated response to continental hydrological dynamics, some authors invert the reasoning and use changes in hydrology as an indicator of global warming (Gleick, 2003; Nilsson *et al.*, 2005; Milliman *et al.*, 2008). These matters relate to forecasts of precipitation variability, floods, and droughts, issues also addressed elsewhere in this chapter.

In a pivotal study of this relationship that formed part of the World Climate Program supported by UNESCO and the WMO, Kundzewicz *et al.* (2004) analyzed long-term and high-quality data on streamflow to determine whether floods have increased worldwide, as predicted by climate models. They concluded, “the analysis of 195 long time series of annual maximum flows, stemming from the GRDC holdings does not support the hypothesis of general growth of flood flows. ... Observations to date provide no conclusive and general proof as to how climate change affects flood behaviour. There is a discontinuity between some observations made so far. Increases in flood maxima are not evident whilst model-based projections show a clear increase in intense precipitation.”

Milliman *et al.* (2008) examined discharge trends over the second half of the twentieth century for 137 rivers whose combined drainage basins represent about 55 percent of world land area. They found “between 1951 and 2000 cumulative discharge for the 137 rivers remained statistically unchanged,” as did global on-land precipitation over the same period.

Munier *et al.* (2012) also estimated global runoff for the period 1993–2009, using two methods both of which were derived by coupling modeled land-atmosphere and ocean-atmosphere water budgets with independent datasets in order to estimate water storage variations in several water budget compartments. The datasets included atmospheric re-

analyses, land surface models, satellite altimetry, and direct ocean temperature measurements. The results of both sets of calculations of global runoff correlate well for the full period 1993–2006. The researchers found “no significant trend ... over the whole period” for either method of calculation. They conclude, “an intensification of the global water cycle due to global warming is not obvious over the last two decades.”

Conclusions

The IPCC hypothesis regarding changes in streamflow should have been tested by these studies, but the hypothesis is so loosely formulated as to be essentially untestable. Predicting global warming will lead to more frequent and/or more intense flooding and drought, as the IPCC does, ensures predictive success for just about any dataset studied for any time and any place.

Nevertheless, none of the Kundzewicz *et al.* (2004), Milliman *et al.* (2008), or Munier *et al.* (2012) studies was able to identify any change in global runoff over the past 60 years. The simplest and most obvious conclusion to draw is that of Milliman *et al.* (2008), who report “neither discharge nor precipitation changed significantly over the last half of the 20th century, offering little support to a global intensification of the hydrological cycle.”

References

- Dai, A., Qian, T.T., Trenberth, K.E., and Milliman, J.D. 2009. Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate* **22**: 2773–2792.
- Gerten, D., Rost, S., von Bloh, W., and Lucht, W. 2008. Causes of change in 20th century global river discharge. *Geophysical Research Letters* **35**: 10.1029/2008GL035258.
- Gleick, P. 2003. Global freshwater resources: soft-path solutions for the 21st century. *Science* **302**: 1524–1528.
- Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* **319**: 83–95.
- Kundzewicz *et al.* 2004. Detection of change in worldwide hydrological time series of maximum annual flow. World Climate Programme—Water, UNESCO-WMO. http://www.bafg.de/GRDC/EN/02_srvcs/24_rprtrs/report_32.pdf?__blob=publicationFile.
- Labat, D. 2004. Evidence for global runoff increase related to climate warming. *Advances in Water Resources* **27**: 631–642.
- Milliman, J.D., Farnsworth, K.L., Jones, P.D., Xu, K.H.

Observations: The Hydrosphere and Oceans

and Smith, L.C. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change* **62**: 187–194.

Munier, S., Palanisamy, H., Maisongrande, P., Cazenave, A., and Wood, E.F. 2012. Global runoff anomalies over 1993–2009 estimated from coupled Land-Ocean-Atmosphere water budgets and its relation with climate variability. *Hydrology and Earth System Sciences* **16**: 3647–3658.

Nilsson, C., Reidy, C., Dynesius, M., and Revenga, C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* **308**: 405–408.

Earlier Research

Here we summarize other studies that address whether late twentieth century warming might have caused changes in streamflow regimes.

- Lins and Slack (1999) analyzed streamflow trends for 395 climate-sensitive stations, including data from more than 1,500 individual gauges, located throughout the United States, the longest datasets stretching back to 1914. They found many more flow up-trends than down-trends, with slight decreases occurring “only in parts of the Pacific Northwest and the Southeast.” Their findings indicate “the conterminous U.S. is getting wetter, but less extreme.”
- Brown *et al.* (1999) studied siliciclastic sediment grain size, planktonic foraminiferal and pteropod relative frequencies, and the carbon and oxygen isotopic compositions of two species of planktonic foraminifera in cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico to delineate the changing characteristics of the Mississippi River over the past 5,300 years. They identified the occurrence of large megafloods—which they describe as having been “almost certainly larger than historical floods in the Mississippi watershed”—at 4,700, 3,500, 3,000, 2,500, 2,000, 1,200, and 300 years before present. These flow events probably related to times of export of extremely moist Gulf air to midcontinental North America, driven by naturally occurring millennial and multidecadal oscillations in Gulf of Mexico ocean currents.
- Hidalgo *et al.* (2000) used principal components analysis to reconstruct streamflow in the Upper Colorado River Basin from tree-ring data, comparing their results with the streamflow reconstruction of Stockton and Jacoby (1976). Their work supported the earlier study but delivered a better understanding of periods of below-average stream-flow or regional

drought. Hidalgo *et al.* identify “a near-centennial return period of extreme drought events in this region” that stretched back to the early 1500s, and their data suggest the existence of past droughts that surpassed the worst of the twentieth century.

- Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to develop annual precipitation and streamflow histories for the period 1651–1995. The research revealed variations over the recent period of instrumental data are not unusual relative to the prior record, as judged against the standard deviation and five-year intervals representative of extreme wet and dry periods. Although the reconstructions “appear to show more frequent extended wet periods in more recent decades,” Pederson *et al.* conclude this observation does not provide “unequivocal evidence of an increase in precipitation as suggested by some climate models.” Spectral analysis of the data also revealed significant periodicities of 12 and 20–24 years, hinting at the presence of a solar influence.
- Knox (2001) studied how conversion of the U.S. Upper Mississippi River Valley from prairie and forest to crop and pasture land in the early 1800s influenced subsequent watershed runoff and soil erosion rates. Initially, the conversion of the region's natural landscape to agricultural use increased surface erosion rates by three to eight times those characteristic of pre-settlement times. The land-use conversion also increased the peak discharges from high-frequency floods by 200 to 400 percent. Since the late 1930s, however, surface runoff has been decreasing. The decrease “is not associated with climatic causes,” according to Knox, who reports an analysis of the variation in storm magnitude over the same period showed no statistically significant trend.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for the period 1948–1997 in a semiarid region of the southwestern United States, the Rio Puerco Basin of New Mexico. They reported “a statistically significant [annually] increasing trend in precipitation in the basin was detected.” This trend was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale; monthly totals increased in low-flow months and decreased in high-flow months.
- Hisdal *et al.* (2001) analyzed more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and

frequency of drought over the following four time periods: 1962–1990, 1962–1995, 1930–1995, and 1911–1995. They concluded, “despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied.” On the contrary, the trends pointing toward decreasing streamflow deficits or fewer droughts outnumbered trends of increasing streamflow deficits or more droughts.

- Cluis and Laberge (2001) checked for recent changes in runoff at 78 rivers “geographically distributed throughout the whole Asia-Pacific region,” using streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany). Mean start and end dates of the river flow records were 1936 ± 5 years and 1988 ± 1 year. The researchers determined mean river discharges were unchanged in 67 percent of the cases investigated; where trends did exist, 69 percent were for lesser flows. Maximum river discharges were unchanged in 77 percent of the cases investigated, and where trends did exist 72 percent were again downward. Minimum river discharges were unchanged in 53 percent of cases investigated; where trends existed, 62 percent of them were upward.
- Campbell (2002) analyzed grain size in 4,000-year-long sediment cores from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of climate variability. The research identified periods of both increasing and decreasing grain size (a proxy for moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales. The predominant departures from the background norm included several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500–1900), the Medieval Warm Period (about AD 700–1300), the Dark Ages Cold Period (about BC 100 to AD 700), and the Roman Warm Period (about BC 900–100). A standardized median grain-size history revealed the highest rates of stream discharge during the past 4,000 years occurred during the Little Ice Age, approximately 300–350 years ago, when grain sizes were about 2.5 standard deviations above the 4,000-year mean. By contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean. Grain size over the past 150 years generally has remained above average, with no indication of a climatic trend related to twentieth century warming.
- McCabe and Wolock (2002) evaluated U.S. records for 1895–1999 for three hydrologic parameters: precipitation minus annual potential evapotranspiration, the surplus water that eventually becomes streamflow, and the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. This investigation revealed a statistically significant increase in the first two of these parameters, and for the third there was no change, indicating water has become more available within the conterminous United States and there has been no increase in the amount of water required for optimum plant growth.
- Pekarova *et al.* (2003) analyzed annual discharge rates of selected large rivers of the world for recurring cycles of wet and dry. For rivers with long enough records, they also derived long-term discharge rate trends. The authors could not identify “any significant trend change in long-term discharge series (1810–1990) in representative European rivers,” including the Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone, and Po.
- McCabe and Clark (2005) used daily streamflow data representing snowmelt for 84 stations in the western United States, each with complete water-year information for the period 1950–2003. Each station’s mean streamflow trend was determined for the past half century as well as any marked steps that may have occurred in each data series. As other researchers had reported previously, McCabe and Clark determined the timing of snowmelt runoff for many rivers in the western United States has shifted earlier, not as a trend but as a step change during the mid-1980s. This change occurred coincidentally with “a regional step increase in April–July temperatures during the mid-1980s.” After discussing the possible reasons for these changes, McCabe and Clark conclude “the observed change in the timing of snowmelt runoff in the western United States is a regional response to natural climatic variability and may not be related to global trends in temperature.”
- Carson and Munroe (2005) used tree-ring data collected by Stockton and Jacoby (1976) from the Uinta Mountains of Utah to reconstruct the mean annual discharge in the Ashley Creek watershed for the period 1637 to 1970. Significant persistent departures from the long-term mean occurred throughout the 334-year record of streamflow. The periods 1637–1691 and 1741–1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows, indicative of persistent drought or near-drought

conditions. By contrast, there was an overall abundance of extremely large flows and relatively few extremely small flows during the periods 1692–1740 and 1898–1945, indicative of wetter conditions.

- Rood *et al.* (2005) analyzed streamflow trends for rivers fed by relatively pristine watersheds in the central Rocky Mountain Region extending from Wyoming (United States) through British Columbia (Canada). Both parametric and nonparametric statistical analyses were used to assess nearly a century of annual discharge (ending about 2002) along 31 river reaches that drain this part of North America. They found river flows in the region declined over the past century by an average of 0.22% per year, with four of them exhibiting recent decline rates exceeding 0.5% per year. This finding “contrasts with the many current climate change predictions that [this] region will become warmer and wetter in the near-future.”

- Déry and Wood (2005) analyzed hydrometric data for 1964–2003 from 64 northern Canadian rivers that drain more than half of the country’s landmass. After assessing variability and trends in the data, they explored the influence of large-scale teleconnections on the data record. They identified a statistically significant mean decline of approximately 10 percent in the discharge rates of the 64 rivers over the four decades of their study, matching a decline in precipitation known for northern Canada between 1964 and 2000. Déry and Wood conclude the decline in river discharge was driven “primarily by precipitation rather than evapotranspiration.” They also report statistically significant links between the declines in precipitation and streamflow and the Arctic Oscillation, the El Niño/Southern Oscillation, and the Pacific Decadal Oscillation. No influence was discerned from twentieth century warming per se.

- Cao *et al.* (2006) conducted a streamflow study for the Qinghai-Tibet Plateau to evaluate theoretical arguments and models that suggest deleterious human-caused changes in streamflow might occur there (Houghton *et al.*, 2001; Rahmstorf and Ganopolski, 1999; Bruce *et al.*, 2002). The modeled scenarios suggest global warming should cause a precipitation increase in northwest China, with one researcher predicting a regional climatic shift from warm-dry to warm-wet (Shi, 2003) accompanied by an increase in total river discharge.

Cao *et al.* analyzed annual discharge data for five large rivers of the Qinghai-Tibet Plateau over the period 1956–2000, using the Mann-Kendall nonparametric trend test. They determined “river

discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the Northern Hemisphere surface air temperature,” and therefore with late twentieth century warming.

- Woodhouse *et al.* (2006) generated updated proxy reconstructions of streamflow for four key gauges in the Upper Colorado River Basin (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona). They determined the major drought of 2000–2004, “as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record,” and “average reconstructed annual flow for the period 1844–1848 was lower.” They also report “two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004,” and six other periods “have a 10% or greater chance of being drier.” They conclude their “analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate” and “droughts more severe than any 20th to 21st century event [have] occurred in the past.”

- Novotny and Stefan (2006) analyzed Nevada (USA) streamflow records prior to 2002 from 36 gauging stations in five major river basins, with lengths ranging from 53 to 101 years. They derived seven annual streamflow statistics: mean annual flow, seven-day low flow in winter, seven-day low flow in summer, peak flow due to snowmelt runoff, peak flow due to rainfall, and high and extreme flow days. Significant trends occurred for each of the seven statistics somewhere in the state, but in most cases the trends are not monotonic but periodic. Not surprisingly, “the mean annual stream flow changes are well correlated with total annual precipitation changes.”

With respect to extreme hydrological events, Novotny and Stefan found peak flood flows due to snowmelt runoff “are not changing at a significant rate throughout the state,” but seven-day low flows or base flows are “increasing in the Red River of the North, Minnesota River and Mississippi River basins during both the summer and winter” and the “low flows are changing at a significant rate in a significant number of stations and at the highest rates in the past 20 years.” They note “this finding matches results of other studies which found low flows increasing in the upper Midwest region including Minnesota (Lins and Slack, 1999; Douglas *et al.*, 2000).”

The changes Novotny and Stefan described are mostly beneficial, because “water quality and aquatic ecosystems should benefit from increases in low

flows in both the summer and winter, since water quality stresses are usually largest during low flow periods.” In addition, they note, “other good news is that spring floods (from snowmelt), the largest floods in Minnesota, have not been increasing significantly.”

- Woodhouse and Lukas (2006) developed a network of 14 annual streamflow reconstructions, 300 to 600 years long, for the Upper Colorado and South Platte River basins, Colorado, based on tree-ring chronologies. The authors conclude “the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries”; and further, “paleoclimatic studies indicate that the natural variability in 20th century [streamflow] gage records is likely only a subset of the full range of natural variability,” as discovered also by Stockton and Jacoby (1976), Smith and Stockton (1981), Meko *et al.* (2001), and Woodhouse (2001). They conclude “multi-year drought events more severe than the 1950s drought have occurred” and “the greatest frequency of extreme low flow events occurred in the 19th century,” with a “clustering of extreme event years in the 1840s and 1850s.”

- Davi *et al.* (2006) used tree-ring-width chronologies from five sampling sites in west-central Mongolia to develop precipitation models. The longest of the five tree-ring records (1340–2002) was used to reconstruct a proxy streamflow record for 1637–1997. Davi *et al.* report there was “much wider variation in the long-term tree-ring record than in the limited record of measured precipitation [1937–2003].” Their streamflow history indicates “the wettest 5-year period was 1764–68 and the driest period was 1854–58,” while “the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83.”

- MacDonald *et al.* (2007) used tree-ring records from northern Eurasia to provide reconstructions back to AD 1800 of annual discharge for the major rivers that enter the Arctic Ocean: S. Dvina, Pechora, Ob’, Yenisey, Lena, and Kolyma. Annual discharges in the mid to late twentieth century were not significantly greater than discharges experienced over the preceding 200 years and “are thus still within the range of long-term natural variability.” MacDonald *et al.* also found “longer-term discharge records do not indicate a consistent positive significant correlation between discharge [and] Siberian temperature,” but instead a weak *negative* correlation over the period of their study.

- St. George (2007) used streamflow data from the

Winnipeg River watershed to assess Burn’s (1994) suggestion that a doubling of the air’s CO₂ content might increase the severity and frequency of droughts in the prairie provinces of Canada (Alberta, Saskatchewan, Manitoba), an assertion that conflicts with climate modeling suggesting runoff in Manitoba instead could increase 20 to 30 percent by 2050 (Milly *et al.*, 2005). St. George assembled streamflow data from nine gauge stations for the period 1924–2003 from the Water Survey of Canada’s HYDAT data archive, with precipitation and temperature data taken from Environment Canada’s Adjusted Historical Canadian Climate Data archive.

St. George’s analysis showed “mean annual flows have increased by 58% since 1924 ... with winter streamflow going up by 60–110%,” primarily because of “increases in precipitation during summer and autumn.” A link to climate is suggested by the fact that similar “changes in annual and winter streamflow are observed in records from both regulated and unregulated portions of the watershed.” However, other studies have reported declining flow for many rivers in the Canadian prairies (Westmacott and Burn, 1997; Yulianti and Burn, 1998; Déry and Wood, 2005; Rood *et al.*, 2005). In essence, conflicting conclusions have been reached about the hydrology of the prairie provinces of Canada, especially in Manitoba, making it impossible to issue confident forecasts about future streamflows. Nonetheless, St. George asserts “the potential threats to water supply faced by the Canadian Prairie Provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin.”

- Smith *et al.* (2007) presented an analysis of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia, with a focus on assessing low-flow trends since the 1930s. They conclude “a clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or ‘low flows,’ have risen in northern Eurasia during the 20th century” with the greatest minimum flow increases since ~1985.

- Mauas *et al.* (2008) studied Parana River, South America, streamflow data since 1904, when the daily record began. The river is the world’s fifth-largest in terms of drainage area and fourth-largest with respect to streamflow. The researchers found “the flow of the Parana is larger in the last three decades, with a mean value almost 20% larger than that of the first 70 years of the twentieth century.” They note “the stream flow during the last 30 years has increased in the months in which the flow is minimum, while the flow remains more or less constant during the months of maximum

... [and] ... the same trend is also found in other rivers of the region.”

Mauas *et al.* also report a strong correlation between solar parameters and periodicities present in the detrended time series of streamflow data. Both sunspot number and total solar irradiance correlate at a significance level greater than 99.99% with Pearson’s correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69 respectively.

- Hannaford and Marsh (2008) utilized a U.K. benchmark network of 87 near-natural catchments (as identified by Bradford and Marsh, 2003) to appraise trends in high-flow regimes in catchments unaffected by human disturbances. They write, “recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments, and projections suggest that flooding may increase in [the] future as a result of human-induced warming.”

The two researchers report “significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK,” with similar changes being absent from lowland areas in the south and east of the U.K. The high-flow indicators they observed in the northwest are correlated with the North Atlantic Oscillation (NAO), suggesting the recent upward trend in high-flow events may reflect one part of a multidecadal cycle.

- Lloyd (2010) studied flow trends in the Breede River, the largest in South Africa’s Western Province and economically significant. Prior modeling studies had predicted flows into the river could be reduced dramatically by a warming climate (e.g., Steynor *et al.*, 2009). Steynor *et al.* analyzed flow data for five sites in the Breede Valley to compute historical flow-rate trends over historic periods of warming ranging from 29 to 43 years in length. All the calculated future flow rates exhibited significant negative change, averaging -25% for one global climate model and -50% for another. The mean past trend of four of the five Breede River stations also was negative (-13%), with the remaining station indicating an increase of +14.6%. Lloyd noted “changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows” of the negative-trend stations.

Because Steynor *et al.* had presumed warming would lead to decreased flow, they assumed their projections were correct. Lloyd was able to demonstrate those results were driven primarily by

unaccounted-for land use changes in the five catchments; the one site that had “a pristine watershed” was the one with the “14% increase in flow over the study period.” Lloyd concluded his results were contrary to the climate change predictions and indicate “climate change models cannot yet account for local climate change effects.”

- Panin and Nefedov (2010) provided a riverine geomorphological and archaeological study of the Upper Volga and Zapadnaya Dvina Rivers (Russia) to assess the hypothesis that human settlement on floodplains is controlled by the frequency of seasonal floods. Their database comprised occupational layers for 1,224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province.

Panin and Nefedov identified a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals associated with periods of warming and cooling, respectively. The period AD 1000–1300 Middle Ages provided particularly favorable conditions for floodplain settlement in areas subject to inundation today. Panin and Nefedov conclude this interval “can be regarded as hydrological analogues of the situation of the late 20th–early current century.” This relationship implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

- Zhang *et al.* (2010) analyzed twentieth century daily streamflow for eight unregulated streams in the Susquehanna River Basin, USA. This basin includes parts of the states of Maryland, New York, and Pennsylvania and is the largest freshwater contributor to Chesapeake Bay, comprising 43 percent of the bay’s drainage area and providing 50 percent of its water. The records studied start at slightly different times, but all end in 2006 with record-lengths ranging from 68 to 93 years and an average length of 82.5 years. The data were subjected to monotonic trend tests, each of which used different beginning and ending times, to detect changes and trends in annual minimum, median, and maximum daily streamflow.

Zhang *et al.* found annual maximum streamflow “does not show significant long-term change,” but there was “a considerable increase in annual minimum flow for most of the examined watersheds, and a noticeable increase in annual median flow for about half of the examined watersheds.”

- Hannaford and Buys (2012) analyzed trends in U.K. river flow between 1969 and 2008 in a network of 89 near-natural catchments in an attempt to distinguish natural climate-driven trends from direct anthropogenic disturbances. Previous model studies have suggested the U.K. will experience wetter winters and hotter, drier summers in the future, causing decreasing river flow in summer and increases in winter (Murphy *et al.* 2009; Arnell, 2011; Prudhomme *et al.*, 2012), with increases in flood frequency and magnitude in some regions (Arnell, 2011; Kay and Jones, 2012; Bell *et al.*, 2012). Real-world data, however, indicate droughts in 2004–2006 (Marsh *et al.*, 2007) and 2010–2012 (Marsh, 2012) were caused by successive dry winters, while a sequence of wet summers occurred in the 2007–2012 period (e.g., Marsh and Hannaford, 2008).

In apparent harmony with climate model projections, Hannaford and Buys observed “an overall increase in winter river flows.” But in conflict with what the models predict, they report “in summer, there is no compelling evidence for a decrease in overall runoff or low flows, which is contrary to trajectories of most future projections.” More specifically, they found the predominance of increasing flow trends across the seasons, coupled with limited decreases in low flows, is favorable from a water management perspective; the lack of any tendency toward decreasing river flow (for summer and for low flows especially) contradicts model expectations under assumed global warming scenarios; and the lack of decreasing river flow indicates a robustness and resilience of hydrology to warming trends.

- Khoi and Suetsugi (2012) evaluated seven climate models—CMIP3 GCMs—CCCMA CGCM3.1, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM3.0, UKMO HadGEM1, and UKMO Had CM3—to determine which was most successful in predicting rates of streamflow in Vietnam’s Be River Catchment. The IPCC’s SRES emission scenarios A1B, A2, B1, and B2 were adopted, along with prescribed increases in global mean temperature ranging between 0.5 and 6°C.

GCMs consistently have projected increases in the frequency and magnitude of extreme climate events, and variability of precipitation, leading some authors to conclude “this will affect terrestrial water resources in the future, perhaps severely” (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Chen *et al.*, 2011). Khoi and Suetsugi’s findings, however, indicate “the greatest source of uncertainty in impact of climate change on streamflow is GCM structure

[choice of GCM],” noting the range of uncertainty could have increased even further if a larger number of GCMs had been deployed. Similar findings have been made by other authors, including Kingston and Taylor (2010), Kingston *et al.* (2011), Nobrega *et al.* (2011), Thorne (2011), and Xu *et al.* (2011). Khoi and Suetsugi conclude “single GCM or GCMs ensemble mean evaluations of climate change impact are unlikely to provide a representative depiction of possible future changes in streamflow.”

Conclusions

There appears to be little support in real-world data for the contention that CO₂-induced global warming will lead to more frequent and/or more severe increases and decreases in streamflow that result in, or are indicative of, more frequent and/or more severe floods and droughts. Observed trends appear to be just the opposite of what is predicted to occur, and nearly all observed real-world changes are either not deleterious or are beneficial, and often extremely so. For example:

- Lins and Slack (1999) report the United States has become wetter in the mean and less variable in the extremes during warming over the last century.
- Brown *et al.* (1999) have shown the 1999 Mississippi floods were not related to changes in atmospheric CO₂.
- Campbell (2002) demonstrates there is nothing unusual about the moisture status of the Alberta region during the past 50 years compared to the record of the last millennium, and Déry and Wood (2005) similarly record no change in river flows in northern Canada over the past 60 years.
- Pekarova *et al.* (2003) show no long-term changes took place in the discharge of European rivers during the past 180 years, which period encompasses the passage between the end of the Little Ice Age and twentieth century climate.
- Cao *et al.* (2006) could detect no increase in stream discharge on the Tibetan Plateau during recent warming, and Davi *et al.* (2006) could find no evidence for any twentieth century long-term change in precipitation or streamflow.

Clearly, real-world data do not support the negative hydrologic effects the IPCC associates with

Observations: The Hydrosphere and Oceans

both real-world and simulated global warming. At the same time, the paper by Khoi and Suetsugi (2012) demonstrates neither single GCMs nor GCM ensembles can currently provide representative estimates of future patterns of streamflow. Moreover, some studies identify solar factors (Brown *et al.*, 1999; Pederson *et al.*, 2001) or multidecadal cyclicity (Hannaford and Marsh, 2008; Mauas *et al.*, 2008) as more important influences on streamflow variability than is atmospheric CO₂.

References

Arnell, N.W. 2011. Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. *Hydrology and Earth System Sciences* **15**: 897–912.

Bell, V.A., Kay, A.L., Cole, S.J., Jones, R.G., Moore, R.J., and Reynard, N.S. 2012. How might climate change affect river flows across the Thames basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *Journal of Hydrology* **442–443**: 89–104.

Bradford, R.B. and Marsh, T.M. 2003. Defining a network of benchmark catchments for the UK. *Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering* **156**: 109–116.

Brown, P., Kennett, J.P., and Ingram B.L. 1999. Marine evidence for episodic Holocene megafloods in North America and the northern Gulf of Mexico. *Paleoceanography* **14**: 498–510.

Bruce, J.P., Holmes, R.M., McClelland, J.W. *et al.* 2002. Increasing river discharge to the Arctic Ocean. *Science* **298**: 2171–2173.

Burn, D.H. 1994. Hydrologic effects of climate change in western Canada. *Journal of Hydrology* **160**: 53–70.

Campbell, C. 2002. Late Holocene lake sedimentology and climate change in southern Alberta, Canada. *Quaternary Research* **49**: 96–101.

Cao, J., Qin, D., Kang, E., and Li, Y. 2006. River discharge changes in the Qinghai-Tibet Plateau. *Chinese Science Bulletin* **51**: 594–600.

Carson, E.C. and Munroe, J.S. 2005. Tree-ring based streamflow reconstruction for Ashley Creek, northeastern Utah: Implications for palaeohydrology of the southern Uinta Mountains. *The Holocene* **15**: 602–611.

Cluis, D. and Laberge, C. 2001. Climate change and trend detection in selected rivers within the Asia-Pacific region. *Water International* **26**: 411–424.

Chen, J., Brissette, F.P., and Leconte, R. 2011. Uncertainty of downscaling method in quantifying the impact of

climate change on hydrology. *Journal of Hydrology* **401**: 190–202.

Davi, N.K., Jacoby, G.C., Curtis, A.E., and Baatarbileg, N. 2006. Extension of drought records for Central Asia using tree rings: West-Central Mongolia. *Journal of Climate* **19**: 288–299.

Déry, S.J. and Wood, E.F. 2005. Decreasing river discharge in northern Canada. *Geophysical Research Letters* **32**: doi:10.1029/2005GL022845.

Douglas, E.M., Vogel, R.M., and Kroll, C.N. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* **240**: 90–105.

Hannaford, J. and Buys, G. 2012. Trends in seasonal river flow regimes in the UK. *Journal of Hydrology* **475**: 158–174.

Hannaford, J. and Marsh, T.J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**: 1325–1338.

Hisdal, H., Stahl, K., Tallaksen, L.M., and Demuth, S. 2001. Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology* **21**: 317–333.

Hidalgo, H.G., Piechota, T.C., and Dracup, J.A. 2000. Alternative principal components regression procedures for dendrohydrologic reconstructions. *Water Resources Research* **36**: 3241–3249.

Houghton, J.T., Ding, Y., and Griggs, D.J. (Eds.) *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.

Kay, A.L. and Jones, D.A. 2012. Transient changes in flood frequency and timing in Britain under potential projections of climate change. *International Journal of Climatology* **32**: 489–502.

Khoi, D.N. and Suetsugi, T. 2012. Uncertainty in climate change impacts on streamflow in Be River Catchment, Vietnam. *Water and Environment Journal* **26**: 530–539.

Kingston, D.G. and Taylor, R.G. 2010. Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. *Hydrology and Earth System Sciences* **14**: 1297–1308.

Kingston, D.G., Thompson, J.R., and Kite, G. 2011. Uncertainty in climate change projections of discharge for Mekong River Basin. *Hydrology and Earth System Sciences* **15**: 1459–1471.

Knox, J.C. 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *Catena* **42**: 193–224.

Climate Change Reconsidered II

- Lins, H.F. and Slack, J.R. 1999. Streamflow trends in the United States. *Geophysical Research Letters* **26**: 227–230.
- Lloyd, P. 2010. Historical trends in the flows of the Breede River. *Water SA* **36**: 329–333.
- MacDonald, G.M., Kremenetski, K.V., Smith, L.C., and Hidalgo, H.G. 2007. Recent Eurasian river discharge to the Arctic Ocean in the context of longer-term dendrohydrological records. *Journal of Geophysical Research* **112**: 10.1029/2006JG000333.
- Marsh, T.J. 2012. UK Hydrological Bulletin: May-July 2012; and Newsletter of the British Hydrological Society, August 2012.
- Marsh, T.J., Cole, G., and Wilby, R. 2007. Major droughts in England and Wales, 1800–2006. *Weather* **62**: 87–93.
- Marsh, T.J. and Hannaford, J. 2008. *The 2007 Summer Floods in England and Wales—A Hydrological Appraisal*. Centre for Ecology and Hydrology, Wallingford, United Kingdom.
- Mauas, P.J.D., Flamenco, E., and Buccino, A.P. 2008. Solar forcing of the stream flow of a continental scale South American river. *Physical Review Letters* **101**: 168501.
- McCabe, G.J. and Clark, M.P. 2005. Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology* **6**: 476–482.
- McCabe, G.J. and Wolock, D.M. 2002. Trends and temperature sensitivity of moisture conditions in the conterminous United States. *Climate Research* **20**: 19–29.
- Meko, D.M., Therrell, M.D., Baisan, C.H., and Hughes, M.K. 2001. Sacramento River flow reconstructed to A.D. 869 from tree rings. *Journal of the American Water Resources Association* **37**: 1029–1039.
- Milly, P.C.D., Dunne, K.A., and Vecchia, A.V. 2005. Global patterns of trends in streamflow and water availability in a changing climate. *Nature* **438**: 347–350.
- Molnar, P. and Ramirez, J.A. 2001. Recent trends in precipitation and streamflow in the Rio Puerco Basin. *Journal of Climate* **14**: 2317–2328.
- Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R.A. 2009. *UK Climate Projections Science Report: Climate Change Projections*. Met Office, Hadley Center, Exeter, United Kingdom.
- Nobrega, M.T., Collischonn, W., Tucci, C.E.M., and Paz, A.R. 2011. Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrology and Earth System Sciences* **15**: 585–595.
- Novotny, E.V. and Stefan, H.G. 2006. Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology* **334**: 319–333.
- Panin, A.V. and Nefedov, V.S. 2010. Analysis of variations in the regime of rivers and lakes in the Upper Volga and Upper Zapadnaya Dvina based on archaeological-geomorphological data. *Water Resources* **37**: 16–32.
- Pederson, N., Jacoby, G.C., D’Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. *Journal of Climate* **14**: 872–881.
- Pekarova, P., Miklanek, P., and Pekar, J. 2003. Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries. *Journal of Hydrology* **274**: 62–79.
- Prudhomme, C., Young, A., Watts, G., Haxton, T., Crooks, S., Williamson, J., Davies, H., Dadson, S., and Allen, S. 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. *Hydrological Processes* **26**: 1115–1118.
- Rahmstorf, S. and Ganopolski, A. 1999. Long-term global warming scenarios computed with an efficient coupled climate model. *Climatic Change* **43**: 353–367.
- Rood, S.B., Samuelson, G.M., Weber, J.K., and Wywrot, K.A. 2005. Twentieth-century decline in streamflow from the hydrographic apex of North America. *Journal of Hydrology* **306**: 215–233.
- Shi, Y. 2003. *An Assessment of the Issues of Climatic Shift from Warm-Dry to Warm-Wet in Northwest China*. Meteorological Press, Beijing.
- Smith, L.C., Pavelsky, T.M., MacDonald, G.M., Shiklomanov, A.I., and Lammers, R.B. 2007. Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle. *Journal of Geophysical Research* **112**: 10.1029/2006JG000327.
- Smith, L.P. and Stockton, C.W. 1981. Reconstructed stream flow for the Salt and Verde Rivers from tree-ring data. *Water Resources Bulletin* **17**: 939–947.
- Srikanthan, R. and McMahon, T.A. 2001. Stochastic generation of annual, monthly and daily climate data: A review. *Hydrology and Earth System Sciences* **5**: 653–670.
- Steynor, A.C., Hewitson, B.C., and Tadross, M.A. 2009. Projected future runoff of the Breede River under climate change. *Water SA* **35**: 433–440.
- St. George, S. 2007. Streamflow in the Winnipeg River basin, Canada: Trends, extremes and climate linkages. *Journal of Hydrology* **332**: 396–411.

Observations: The Hydrosphere and Oceans

Stockton, C.W. and Jacoby Jr., G.C. 1976. Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin based on tree-ring analysis. *Lake Powell Research Project Bulletin* **18**. Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

Thorne, R. 2011. Uncertainty in the impacts of projected climate change on the hydrology of a subarctic environment: Laird River Basin. *Hydrology and Earth System Sciences* **15**: 1483–1492.

Westmacott, J.R. and Burn, D.H. 1997. Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. *Journal of Hydrology* **202**: 263–279.

Woodhouse, C.A. 2001. Tree-ring reconstruction of mean annual streamflow for Middle Boulder Creek, Colorado, USA. *Journal of the American Water Resources Association* **37**: 561–570.

Woodhouse, C.A., Gray, S.T., and Meko, D.M. 2006. Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research* **42**: 10.1029/2005WR004455.

Woodhouse, C.A. and Lukas, J.J. 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change* **78**: 293–315.

Xu, C.Y. and Singh, V.P. 2004. Review on regional water resources assessment models under stationary and changing climate. *Water Resources Management* **18**: 591–612.

Xu, H., Taylor, R.G., and Xu, Y. 2011. Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China. *Hydrology and Earth System Sciences* **15**: 333–344.

Yulianti, J. and Burn, D.H. 1998. Investigating links between climatic warming and low streamflow in the Prairies region of Canada. *Canadian Water Resources Journal* **23**: 45–60.

Zhang, Z., Dehoff, A.D., Pody, R.D., and Balay, J.W. 2010. Detection of streamflow change in the Susquehanna River Basin. *Water Resources Management* **24**: 1947–1964.

6.2. Oceans

Key Findings

The main findings of Section 6.2, Oceans, are:

- **SEA-LEVEL CHANGE.** Sea-level rise is one of the most feared impacts of any future global warming, but public discussion of the problem is beset by poor data, misleading analysis, an

overreliance on computer model projections, and a failure to distinguish between global and local sea-level change—all of which has led to unnecessary and unjustified alarm.

- **GEOLOGICAL CONTEXT OF SEA-LEVEL CHANGE.** The maximum sustained rate of global sea-level rise during the most recent postglacial melting was about 10 mm/year, or 1 m/century. The main contributions to this rapid rate of rise, which occurred between about 20,000 and 10,000 years ago, came from melting of continental ice caps over North America and northwest Europe. Such ice caps no longer exist, and therefore a value of 10 mm/y is a realistic natural limit for the likely maximum rate of future sea-level rise should further ice melting ensue. More probably, rates will lie close to the observed twentieth century rate of sea-level rise of ~1.8 mm/y from all causes.
- **DISTINGUISHING LOCAL FROM GLOBAL (EUSTATIC) SEA LEVEL.** Virtually all public discussion that considers sea-level hazard is concerned with changes in the global average sea level. This notional statistic has little relevance to the practicalities of coastal planning and shoreline defense that are the concern of coastal engineers. Real-world coastal management is based upon knowledge of the rate of change of the local relative sea level at the site concerned. Local sea level is influenced as much by substrate subsidence or uplift, sediment supply, and meteorological and oceanographic factors as it is by the notional global average sea level. As it has been in the past, coastal hazard policy should be based upon local relative sea-level change as measured by appropriate and site-specific tide gauges, rather than upon speculative, model-driven prognostications of global average change.
- **TIDE GAUGE MEASUREMENTS.** Many studies of tide gauge datasets conclude the twentieth century saw a progressive rise in global sea level of between about 1.4 and 1.8 mm/y, modulated at a decadal or multidecadal scale by periods of lesser and greater rates of rise. Such conclusions, however, are based upon corrected tide gauge data, and some analyses of uncorrected data indicate a rate of rise of less than 1 mm/y.
- **SATELLITE MEASUREMENTS.** Satellite-mounted measurements of sea level made by radar

ranging altimetry have been available since the early 1990s. Until recently, these measurements indicated a rate of global sea-level rise of more than 3 mm/y; i.e., about twice the rate measured by tide gauges. Over the past few years, however, the satellite-measured rate of rise has been closer to 2 mm/y, a figure that may overlap with the tide gauge measurements once errors are taken into account. Nonetheless, and to the degree they continue to indicate higher rates of sea-level rise than do tide gauge datasets, radar altimetric estimates of sea-level change should be treated circumspectly, for the complexity of their processing is so high the accuracy of the method has yet to be fully established.

- **NATURAL SEA-LEVEL VARIABILITY.** Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and control the oceans' response to atmospheric pressure. These processes vary on decadal and multidecadal time scales, especially with regard to a 60-year-long oceanographic cycle, which vitiates the usefulness of fitting linear trends to sea-level data over periods of less than about 120 years. The pitfall is especially great when shorter periods of time are used to infer an acceleration or deceleration of sea-level rise has occurred, because the existence of such rate changes is an intrinsic part of known natural multidecadal variability. Natural variability must be taken into account during any projection of future sea levels, yet scientists only recently have begun to incorporate it into their modeling.
- **ACCELERATION OF SEA-LEVEL RISE.** The IPCC's 2007 report projected global sea level was likely to rise by somewhere between 18 and 59 cm by 2100, and at an accelerating rate. Since then, several semi-empirical model analyses have predicted sea-level rises for the twenty-first century might even exceed one meter. However, multiple analyses of tide gauge and satellite records make it clear rates of global rise around 10 mm/y do not, and are not likely to, occur. Nearly all sea-level records show either a steady state of rise or a deceleration during the twentieth century, both at individual locations and for the global average. Though it is only an inadequate 20 years long, the satellite radar altimeter record also displays a recent deceleration of sea-level rise.
- **DROWNING ATOLLS.** On October 17, 2009, members of the Maldives' Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to oceanic atolls and islands. In contrast, observational and field evidence from a wide geographic range of low-lying ocean islands show low rates of sea-level rise consonant with the tide gauge global average. An oceanic atoll represents a dynamic sedimentary system sustained by broken coral detritus. Atoll integrity is jeopardized when subjected to human environmental pressures such as sand mining, construction project loading, and rapid groundwater withdrawal, all of which cause local lowering of the ground surface. It is these processes in combination with episodic natural hazards such as king tides and storms, not sea-level rise, that provide the alarming footage of marine flooding on Pacific Islands that from time to time appears on television news.
- **ISOSTASY.** The gravitational load induced on Earth's crust by growth of an ice sheet causes depression of the substrate and local sea-level rise; equally, ice cap melting removes the load and induces uplift and local sea-level fall. This effect is termed isostasy and must be corrected for in global sea-level estimates, generally by using an appropriate Glacial Isostatic Adjustment (GIA). GIA models lack independent verification but are informed by the best-available knowledge of Earth's actual shape, as measured from space in the form of a Terrestrial Reference Frame (TRF). Recently, NASA has indicated current TRF errors are greater than the inferred signal of sea-level change being measured, and the agency has proposed a new satellite be launched with the specific role of measuring the TRF accurately. Clearly, estimates of sea-level change made using satellite-borne altimetric data will remain problematic until the launch of NASA's new GRASP satellite, or until the development of some other mechanism for improving the accuracy of geoid models. As Wunsch *et al.* (2007) noted, "At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology."
- **MODELS.** Semi-empirical and GCM models of future sea-level change project a logarithmically increasing rate of rise. Their proponents argue that although current sea-level change is slow, this is

Observations: The Hydrosphere and Oceans

because the response to temperature has a significant time lag and rates will become progressively faster (10 mm/y or more) in the future. In addition, it is assumed, without justification, that a projected global sea-level curve is also representative of local and regional sea-level changes. The controversy surrounding the likely accuracy and policy usefulness of published semi-empirical and GCM models of sea-level change remains unresolved. Given that simple empirical projections yield more modest projections of future sea level, semi-empirical and GCM model projections indicating higher and increasing rates of rise must be treated as speculative until their known flaws have been addressed.

- **MELTING ICE.** Accurate measures of the global area of sea ice and the volume of onland ice are available only for the satellite era, commencing in 1979. The complexity of correcting and interpreting data measured from near-Earth space is high, and hence significant uncertainty still attends our knowledge of the water balance of the world's oceans with respect to the melting of onland ice. Nonetheless, no strong evidence exists that either the Greenland or Antarctic ice sheet is wasting at greater than natural rates. Little recent change in global sea level can be attributed to enhanced melting of the modern ice sheets. For Antarctica such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall; in such circumstances the sum of the response of the whole Antarctic Ice Sheet might compensate for any long-term wastage of the Greenland Ice Sheet that might occur. As both Antarctica and Greenland have been cooling for the past half-century, it remains entirely possible the global cryosphere is actually growing in mass.
- **OCEAN HEAT.** At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 16 years of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming. Increasingly, this problem has been finessed by noting the atmosphere holds only a small percentage of the world's heat, and that what counts is the 93 percent of global heat sequestered in the oceans.

Accurate measurements of ocean heat are available only since the 2003 deployment of the Argo system of diving buoys. The available Argo record shows no significant or accelerated ocean warming over the past nine years.

- **OCEAN CIRCULATION.** It has been asserted global warming will change the speed of major ocean currents such as the Gulf Stream in ways that will make the world's climate less hospitable. Worries also exist that onland ice melting could deliver enhanced volumes of freshwater to the Arctic Ocean and thereby shut down the critical source of sinking saline water that feeds deep water into the world ocean's thermohaline circulation. All components of ocean circulation vary naturally in flow volume or speed, and often in sympathy with climatic factors. No evidence exists for changes in the global ocean circulation system that lie outside the bounds of natural variation. Though this natural variation has yet to be fully described, evidence is lacking for any additional changes in circulation forced by human CO₂ emissions.

Introduction

To assess whether enhanced freshwater delivery to the Arctic Ocean by increased river flow could shut down the ocean's thermohaline circulation, Peterson *et al.* (2002) plotted annual values of the combined discharge of the six largest Eurasian Arctic rivers—Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina, which drain about two-thirds of the Eurasian Arctic landmass—against the globe's mean annual surface air temperature (SAT). They determined a simple linear regression trend through the data and concluded the combined discharge of the six rivers rises by about 212 km³/year in response to a 1°C increase in mean global air temperature. For the high-end global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) to occur by AD 2100—i.e., a temperature increase of 5.8°C—they projected the warming-induced increase in freshwater discharge from the six rivers could rise by as much as 1,260 km³/year (we calculate 5.8°C x 212 km³/year/°C = 1230 km³/year), a 70 percent increase over the mean discharge rate of the past several years.

It has been hypothesized that the delivery of such a large addition of freshwater to the North Atlantic Ocean may slow or even stop that location's production of new deep water, which constitutes one

of the driving forces of the thermohaline circulation, the great oceanic “conveyor belt.”

Although still discussed, this scenario is not as highly regarded today as it was when Peterson *et al.* conducted their research, for several reasons. For one, it is difficult to accept the tremendous extrapolation Peterson *et al.* make in extending their Arctic freshwater discharge vs. SAT relationship to the great length implied by the IPCC’s predicted high-end warming of 5.8°C over the remainder of the current century. According to Peterson *et al.*, “over the period of the discharge record, global SAT increased by 0.4°C.” It is implausible to extend the relationship they derived for that small temperature increase fully 14-and-a-half times further, to 5.8°C.

Consider also the Eurasian river discharge anomaly vs. global SAT plot of Peterson *et al.* (their Figure 4), which we have re-plotted in Figure 6.2.1. Enclosing their data with simple straight-line upper and lower bounds, it can be seen the upper bound of the data does not change over the entire range of global SAT variability, suggesting the upper bound corresponds to a maximum Eurasian river discharge rate that cannot be exceeded in the real world under its current geographic and climatic configuration. The lower bound, by contrast, rises so rapidly with increasing global SAT that the two bounds intersect less than two-tenths of a degree above the warmest of Peterson *et al.*’s 63 data points, suggesting 0.2°C beyond the temperature of their warmest data point

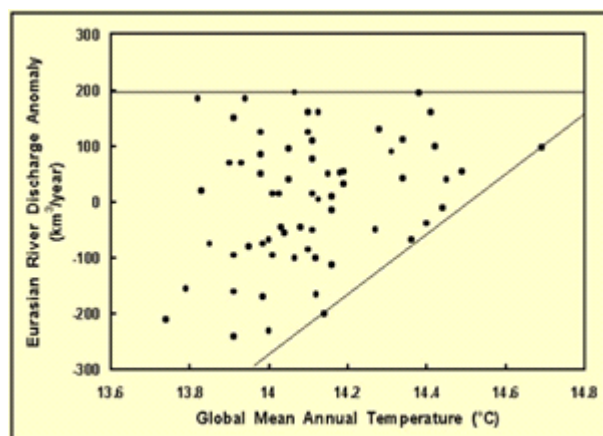


Figure 6.2.1. Annual Eurasian Arctic river discharge anomaly vs. annual global surface air temperature (SAT) over the period 1936 to 1999. Adapted from Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.

may be as far as any relationship derived from their data may be validly extrapolated.

Reference

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.

6.2.1. Sea-level Change

Sea-level rise is one of the most feared impacts of any future global warming (Nicholls, 2011). But public discussion of the problem is beset by poor data, misleading analysis, and an overreliance on computer model projections, leading to unnecessary alarm.

A proper understanding of the risks associated with sea-level change can be attained only by maintaining a clear distinction between changes in global sea level (often also called eustatic sea level) and changes in local relative sea level. Sea-level changes are measured relative to a defined reference level, or datum. This datum is difficult to define over regional and global scales because Earth’s surface is not static; it deforms at different rates and scales in different places. At any one time, the sum of such dynamics controls the volume of the global ocean basin and, therefore, for a fixed volume of seawater, dictates the average sea level worldwide. At the same time, and because both the dynamic Earth surface and the volume of seawater change through time, in combination they also control the multiplicity of local rates of sea-level change we actually observe.

The possibility of large and damaging sea-level rises caused by human-related global warming features prominently in presentations by those who call for urgent action to “stop” global warming, such as former U.S. Vice President Al Gore (Gore, 2006).

Past sea-level positions are measured or inferred from geological evidence. Factual observations regarding modern sea level and its change are traditionally made using tide gauges. Since the early 1990s, modern sea level also has been measurable independently by radar-ranging from satellites.

When data from these sources are analyzed, rates of sea-level change, either rises or falls, are found to vary through time and space (geography), and often quite dramatically over geological time scales. We discuss below several matters relevant to the assertion of both natural and possible human-caused sea-level rise, organizing the discussion into sections that

Observations: The Hydrosphere and Oceans

address observations, modeling, mechanisms, and policy. *Inter alia*, we examine historical trends in sea level to see if any recent increase has occurred in global sea level in response to the supposedly unprecedented warming of the planet over the twentieth century; discuss the proposed scenarios whereby either melting ice or a warming ocean might cause sea levels to rise; and consider the important questions of decadal and multidecadal variability in rates of sea-level change, including both accelerations and decelerations of the rate of change.

the oceanic oxygen isotope record (e.g., Lisiecki and Raymo, 2006; see Figure 6.2.1.1.1). This curve is based on the measured ratio of two isotopes, ^{16}O and ^{18}O , that are fractionated in seawater and hence vary in the shells of fossil animals that lived in that water in accordance with fluctuations of global ice volume through time. High-resolution (millennial) oxygen isotope curves from all ocean basins and latitudes contain a common signal pattern that has become a standard for subdividing Quaternary time into climatic Marine Isotope Stages (MIS), numbered backwards through time. The present interglacial

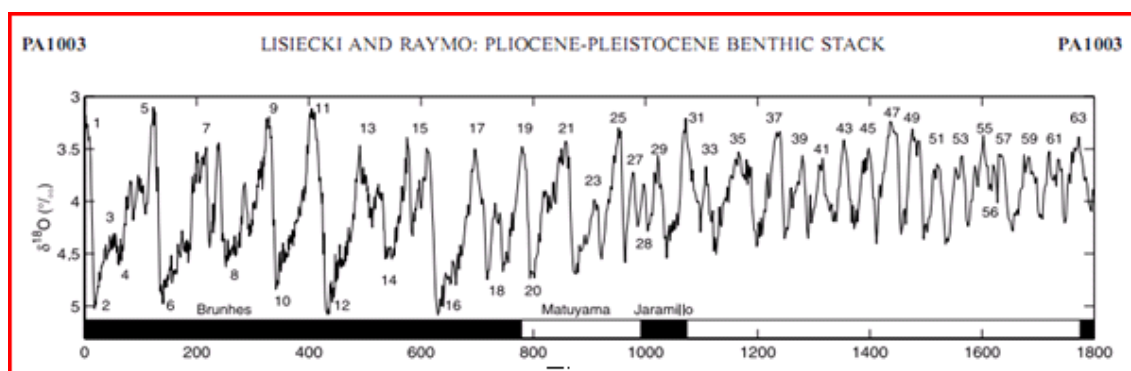


Figure 6.2.1.1.1. Oxygen isotope curve showing the major climatic fluctuations of the last 1.8 million years; numbered peaks indicate Marine Isotope Stages, with even numbers corresponding to ice ages and odd numbers to warm interglacials. A full glacial-interglacial range, say between MIS 12 and MIS 11, represents about 120 m of sea-level change. The apparent anomaly of MIS 3 carrying the designation that otherwise equates to a full interglacial interval stems from the early belief that ice ages were paced by variations in the Earth's 41,000 obliquity cycle. Adapted from Lisiecki, L.E. and Raymo, M.E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20: PA1003. doi: 10.1029/2004PA001071.

References

Gore, A. 2006. *An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It*. Rodale Press, Emmaus, Pennsylvania.

Nicholls, R.J., 2011. Planning for the impacts of sea-level rise. *Oceanography* 24(2): 144–157.

6.2.1.1. Geological studies

Changes in sea level over long periods of time (millions of years) are inferred from geological evidence. By their nature, most such records are of local relative change, and they require correction if they are to be translated into eustatic estimates (e.g., Kominsz *et al.*, 1998).

For about the past 3 million years a high-quality proxy record for eustatic sea level is represented by

(termed the Holocene and defined as starting 11,700 years ago) is effectively synonymous with MIS 1.

The last ice age reached its peak about 20,000 years ago, at which time sea level stood at about -120 m with respect to today. Efforts have been made to reconstruct a global sea-level curve for the period since then, based on careful geological sampling and dating of sea-level-related materials such as mangroves or coral reefs. The resulting curve, in Figure 6.2.1.1.2, shows very rapid melting, at rates up to 26 mm/y over short periods between about 15,000 and 10,000 years ago, after which the rate of rise lessens to 1–2 mm/y in the Holocene.

It is important to note glacio-isostatic effects may have distorted or invalidated the key proxy sea-level records that have been used to construct Figure 6.2.1.1.2 and similar post-glacial sea-level curves (Gehrels, 2010). For example, Bowen (2010) has shown tectonic effects have resulted in a range of

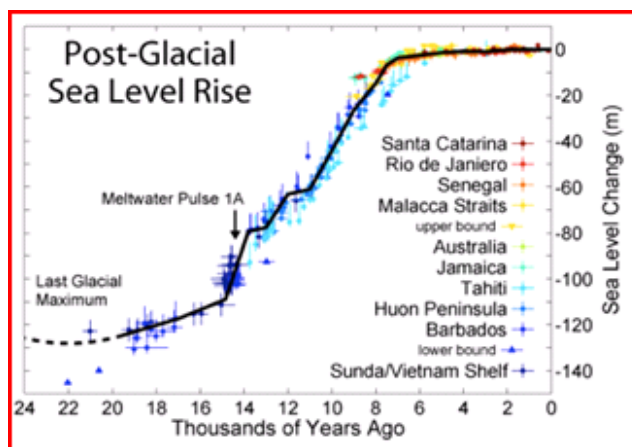


Figure 6.2.1.1.2. Reconstructed global sea-level since the Last Glacial Maximum, 20,000 years ago, based on dated worldwide coral and peat deposits. Adapted from Fairbanks, R.G. 1989. A 17,000 year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**: 637–642; Toscano, M.A. and Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmate* framework and intertidal mangrove peat. *Coral Reefs* **22**: 257–270.

estimates for sea level during warm interglacial MIS 11, most of which do not support the high +20 m level some previous authors have estimated but instead lie closer to present day sea level. It is the presence of significant regional variations in the timing and shape of the sea-level curve, particularly over the past 7,000 years, that led Gehrels (2010) to suggest “‘Eustasy’ is therefore merely a concept, not a measurable quantity.”

Ignoring these geological perspectives, the first reports by the IPCC claimed human-forced sea-level rise could reach as high as 2–3 m by the year 2100 (Hoffman *et al.*, 1983; Kaplin, 1989). Although subsequent IPCC reports have lowered the sea-level rise estimate to something more realistic, individual authors continue to promulgate potential sea-level rises of 1–2 m or more by 2100 AD, supposedly caused by exceptional melting of ice in the Greenland and Antarctic ice caps (e.g., Rapley, in Doyle, 2007; Rahmstorf, 2007).

Hansen and Sato (2011) claimed sea level will rise 5 m by 2100 AD and proposed an exponential increase in glacier melting would produce a 4 m rise in sea level in the 20-year period from 2080 to 2100, a rate of 200 mm/year. These frenetic estimates are

made notwithstanding that the Antarctic ice cap has expanded, not decreased, in the past 20 years (see Chapter 5) and the Greenland ice cap was about the same size as today during the 2.5 °C warmer Holocene Climatic Optimum (Willerslev *et al.*, 2007).

In a number of papers Nils-Axel Mörner (1983, 2004, 2011) has established a maximum possible glacial eustatic rate of change of 10 mm/yr, or 1.0 m/century, derived from the rates that occurred during the glacial eustatic rise after the last glaciation maximum (LGM) of the Last Ice Age at around 20 ka with a sea-level lowstand of about 120 m. The main contribution to the large post-glacial rise in sea level came from melting of the continental ice caps over North America and northwest Europe. a value of 10 mm/yr sets a realistic natural frame for possible maximum rates of modern sea-level rise that might ensue should ice-cap melting quicken.

More generally, it is important to address critically the degree to which sea-level changes on geological timescales can be used to predict future change. Past changes are reconstructed from geologic and geomorphic evidence along coastlines and from inferences drawn about changing ocean geochemistry ($^{18}\text{O}/^{16}\text{O}$ ratios measured on marine microfossils in cores). These are very different lines of evidence, and interpretation of the geochemical studies is further complicated by shifting isotope ratios being caused not only by temperature, but also by water exchanged between the oceans and ice caps during climate cycling. While the temperature term can be removed for some samples using Mg/Ca measurements, the hydrographic effect remains uncertain. Therefore, while an averaged $\delta^{18}\text{O}$ signal of global variability provides an overall indication of the magnitude of glacials and interglacials, as shown in Figure 6.2.1.1.1 above, it is difficult to be confident such data can provide an accurate guide to sea-level variability when differences of at most a few meters are involved for future prediction.

Similar uncertainty presents itself when estimates of lowered sea level and its timing are estimated for the Last Glacial Maximum in order to calibrate sea-level change represented in the $\delta^{18}\text{O}$ record. Lowstand estimates range from -130 m at 20,000 yrs ago (Yokoyama *et al.*, 2000) to -120 m 26,000 yrs ago (Peltier and Fairbanks, 2006). These differences may be caused by regional variability (Elderfield *et al.*, 2012), but they make clear the difficulty of acquiring accurate sea-level estimates. Estimates derived from calculating the effects of glacial isostatic readjustment (GIA) after the last ice age, especially for far field locations, are uncertain. Variability in time and space

Observations: The Hydrosphere and Oceans

of the water content of the mantle (especially olivine) influences its viscosity, which in turn controls isostatic response and is poorly understood (Jones *et al.*, 2012).

Conclusions

Geological evidence provides an important knowledge framework but seldom offers the accuracy and precision needed to inform estimates in the decimeter to several-meter range likely to apply to near-future sea-level rise. Moreover, projections of sea-level change out to 2100 AD must be considered within the framework set by the known maximum rate of post-glacial sea-level rise, 10 mm/yr (1 m/century). Likely rates of future sea-level rise following melting of the Greenland and/or Antarctic ice caps fall well below this 10 mm/yr figure and probably will lie close to the observed modern level of sea-level rise of ~1.8 mm/yr from all causes.

References

Bowen, D.Q. 2010. Sea level ~400,000 years ago (MIS 11): an analogue for present and future sea-level. *Climate of the Past* **6**: 19–29.

Doyle, A. 2007. Antarctic ice thawing faster than predicted. Reuters, 22 August. <http://www.reuters.com/article/2007/08/22/environment-climate-antarctica-dc-idUSL2210716920070822>.

Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I.N., Hodell, D., and Piotrowski, A.M. 2012. Evolution of ocean temperature and ice volume through the mid-Pleistocene climate transition. *Science* **337**: 704–709.

Fairbanks, R.G. 1989. A 17,000 year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**: 637–642.

Gehrels, R. 2010. Sea-level changes since the last glacial maximum: an appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science* **25** (1), 26–38. doi:10.1002/jqs.1273.

Hansen, J.E. and Sato, M., 2011. Paleoclimate implications for human-made climate change. www.columbia.edu/~jeh1/mailings/2011/.

Hoffman, J.S., Keyes, D., and Titus, J.G., 1983. *Projecting future sea-level rise: methodology, estimates to the year 2100, and research needs*. United Nations Environmental Programme.

Jones, A.G., Fullea, J., Evans, R.L., and Miller, M.R. 2012. Water in cratonic lithosphere: calibrating laboratory determined models of electrical conductivity of mantle

minerals using geophysical and petrological observations. *Geochemistry, Geophysics, Geosystems* (AGU) **13**: Q06010, doi: 10.1029/2012GC004055.

Kaplin, P.A. 1989. *Shoreline Evolution During the Twentieth Century: Oceanography, 1988*. UNAM Press, Mexico.

Kominz, M.A., Miller, K.G., and Browning, J.V. 1998. Long-term and short-term global Cenozoic sea-level estimates. *Geology* **26**: 311–314.

Lisiecki, L.E. and Raymo, M.E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* **20**: PA1003. doi: 10.1029/2004PA001071.

Mörner, N.-A. 1983. Sea level. In: Gardner, R.A.M. and Scoging, H. (Eds.) *Mega-Geomorphology*. Oxford University Press, Oxford, p. 79–92.

Mörner, N.-A. 2004. Estimating future sea level changes. *Global Planetary Change* **40**: 49–54.

Mörner, N.-A. 2011. The Maldives: a measure of sea level changes and sea level ethics. *Evidence-Based Climate Science*. Elsevier Inc., doi: 10.1016/B978-0-12-385956-3.10007-5, pp. 197–210.

Peltier, W.R. and Fairbanks, R.G. 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews* **25**: 3322–3337.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea level rise. *Science* **315**: 368–370.

Toscano, M.A. and Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmate* framework and intertidal mangrove peat. *Coral Reefs* **22**: 257–270.

Willerslev, E., *et al.* 2007. Ancient biomolecules from deep ice cores reveal a forested southern Greenland. *Science* **317**: 111–114.

Yokoyama, Y., Lambeck, K., De Dekkar, P., Johnston, P., and Fifield, L.K. 2000. Timing of Last Glacial Maximum from observed sea level minima. *Nature* **406**: 713–716.

Earlier Research

Summarized briefly below are other recent papers that approach the sea-level issue from a geological viewpoint.

- Mörner (2004) noted “prior to 5000–6000 years before present, all sea-level curves are dominated by a general rise in sea level in true glacial eustatic response to the melting of continental ice caps”; given the slowdown of this process thereafter, “sea-level

records are now dominated by the irregular redistribution of water masses over the globe ... primarily driven by variations in ocean current intensity and in the atmospheric circulation system and maybe even in some deformation of the gravitational potential surface.” With respect to the past 150 years, Möerner reports the mean eustatic rise in sea level for the period 1850–1930 was 1.0–1.1 mm/year, but “after 1930–40, this rise seems to have stopped until the mid-1960s (Pirazzoli *et al.*, 1989; Möerner, 1973, 2000).” Thereafter, with the advent of the TOPEX/Poseidon mission, Möerner notes “the record can be divided into three parts: (1) 1993–1996 with a clear trend of stability, (2) 1997–1998 with a high-amplitude rise and fall recording the ENSO event of these years and (3) 1998–2000 with an irregular record of no clear tendency.” Importantly, Möerner concludes “there is a total absence of any recent ‘acceleration in sea-level rise’ and, therefore, ‘no fear of any massive future flooding as claimed in most global warming scenarios.’”

- The PALeo SEA Level Working Group (PALSEA, 2009, 2012) of 32 experienced researchers was convened to examine and summarize the records of recent geological scale sea-level change to provide context for speculations regarding future sea-level rise. With respect to the IPCC’s estimate that global warming between 1.1°C and 6.3°C will occur in the twenty-first century, the group points out the last global warming of comparable magnitude occurred during the termination of the last glacial period. That warming consisted of a series of short, sharp steps on millennial to centennial timescales, the magnitude and rate of warming of which are closely analogous to those of the anthropogenic warming predicted to occur over the coming centuries. This comparison immediately rules out any type of exponentially increasing sea-level response, pointing more toward an asymptotic response where sea-level rise is high initially but gradually levels off (Figure 6.2.1.1.3).

Extending the time scale to the 11,700-year Holocene period, the PALSEA team identified rapid warming and eustatic sea-level rise between 9 and 8.5 ka BP and 7.6 and 6.8 ka BP (increases of 1.3 and 0.7 m per century, respectively). Although a “rapid demise of ice sheets in a climate similar to today is certainly a possibility,” they note, “an improved understanding of ice sheet dynamics is required before one can conclude that the Greenland or West Antarctic ice sheets will behave in a similar fashion in the future.” The PALSEA group noted peak sea levels during the last interglacial period were about 3–6 m above modern sea level at 126 ka BP but attained

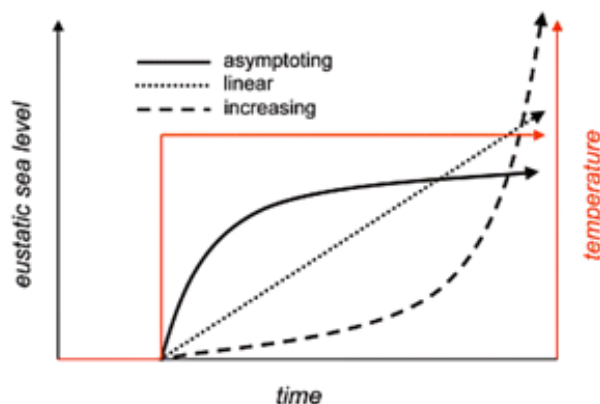


Figure 6.2.1.1.3. Three alternative models for sea-level rise. Adapted from PALSEA, 2009. The sea-level conundrum: case studies from palaeo-archives: *Journal of Quaternary Science* 25: 19–25.

these highs only “several thousand years after proxy records of temperature reached interglacial levels.”

Overall, if the worst-case warming scenario of the IPCC were actually to occur, the PALSEA scientists conclude the likely sea-level rise would lie between the lower limit of twentieth century sea-level rise (0.12 m per century) and sea-level rise at the conclusion of the last glacial period (1 m per century).

- Yokoyama and Esat (2011) note climate change does not always produce a measurable sea-level response, but when it has, that response was rapid and usually accompanied by shifts in ocean circulation.
- Stanford *et al.* (2011) found the most likely maximum rates of sea-level rise during the post-glacial melting ranged from 13 to 15 mm/y, perhaps peaking at 26 mm/y for short periods (decades at most). The maximum rates of rise occurred in two short bursts, referred to as melt-water pulses, that appear to be linked to breakout floods from large Northern Hemisphere pro-glacial lakes. As no large meltwater lakes exist today, such high rates of rise are unlikely to be repeated.

Conclusions

The conclusions drawn from geological evidence contradict the logarithmically increasing sea-level response assumed by the empirical and semi-empirical models used by the IPCC. Some researchers have used the output of these models to generate alarm by saying currently observed sea-level change is slow only because of a lagged response to temperature forcing; they contend sea-level rise will become progressively faster (10 mm/y or more) in the

future. Furthermore, some researchers assume, without justification, that a projected global eustatic sea-level curve is indicative of local or regional sea-level changes.

Natural geological constraints mean predictions of sea-level changes between now and 2100 AD must fall within the frames set by the post-last-glaciation-maximization rates of sea-level rise: less than 10 mm/yr. Any near-future rate of melting of the Greenland and/or Antarctic ice caps is likely to fall well below the rate of the major post-glacial warming.

References

Mörner, N.-A. 1973. Eustatic changes during the last 300 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 13: 13: 1–14.

Mörner, N.-A. 2004. Estimating future sea-level changes from past records. *Global and Planetary Change* 40 (1–2): 49–54.

Mörner, N.-A. 2011. The Maldives: a measure of sea level changes and sea level ethics. *Evidence-Based Climate Science*. Elsevier Inc., doi: 10.1016/B978-0-12-385956-3.10007-5, pp. 197–210.

Mörner, N.-A. 2012. Sea level is not rising. *SPPI Reprint Series*.

PALSEA, 2009. The sea-level conundrum: case studies from palaeo-archives: *Journal of Quaternary Science* 25: 19–25.

PALSEA, 2012. Sea level and ice sheet evolution. De Menocal, P. (Ed.) *Earth and Planetary Science Letters, Special Edition* 315–316: 1–102.

Pirazzoli, P.A., Montaggioni, L.F., Saliege, J.F., Segonzac, G., Thommeret, Y., and Vernaud-Grazzini, C. 1989. Crustal block movement from Holocene shorelines: Rhodes Island (Greece). *Tectonophysics* 170: 89–114.

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., and Lester, A.J. 2011. Sea-level probability for the last deglaciation: a statistical analysis of far-field records.” *Rapid Climate Change: Lessons from the Recent Geological Past* 79 (3–4) (December): 193–203. doi:10.1016/j.gloplacha.2010.11.002.

Yokoyama, Y. and Esat, T.M. 2011. Global climate and sea-level: enduring variability and rapid fluctuations over the past 150,000 years. *Oceanography* 24 (2): 54–69.

6.2.1.2. Tide gauges

Local relative sea level traditionally has been measured at ports using tide gauges, some of which have records extending back to the eighteenth century (see Figure 6.2.1.2.1). These measurements tell us

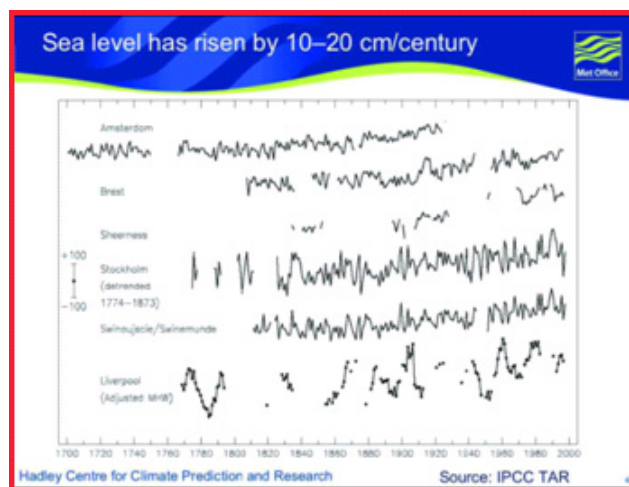


Figure 6.2.1.2.1. Long, northern hemisphere tide gauge records of sea-level change, 1700–2000. Adapted from Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001. 3rd Assessment Report of the IPCC*.

about the change occurring in actual sea level at particular coastal locations, including rises in some places and falls at others. After correcting for any site-specific tectonic or oceanographic-meteorologic distortions of the underlying eustatic sea-level signal, a number of geographically dispersed tide gauge records can be averaged to provide an estimate of the global sea-level curve.

Tide gauges measure water-level oscillations, not merely changes in mean sea level. Various techniques are used to filter out the influence of unwanted oscillations (Pugh, 2004). The tide gauge is constructed in such a way that the instrument gives a limited response to short-duration oscillations such as swell waves and vessel wakes. Numerical techniques are used to extract the oscillations of interest. The analysis generally is optimized to extract tidal constituents, which is not ideal for assessing long-term sea-level changes, particularly since some tidal constituents have periods of years to decades.

After correcting for these factors and for subsidence or uplift, the longer-term tide-gauge records indicate a twentieth century sea-level rise of +1–2 mm/y. Based on these records, the IPCC (2001) estimated an average rate of eustatic rise between 1900 and 2000 of 1.6 mm/y. However, the derivation of such a rate of change is usually achieved by least-squares linear trend analysis. Such calculations are highly sensitive to the start and end points selected for the dataset being considered, and they ignore short-term and multidecadal changes in sea level known to be associated with meteorological and oceanographic

oscillations such as ENSO and the Pacific Decadal Oscillation.

Despite the “consensus” adoption of 1.6–1.8 mm/y as the most likely rate of sea-level rise estimated from tide gauge records, Goddard (2013) recently has shown a straight averaging of the trends of the 159 tide gauge records represented in the NOAA tidal database indicates a much lower figure of only 0.7 mm/y. Similarly low rates of 0.5–1.2 mm/y over historic or late Holocene periods also have been reported by several other authors (Burton, 2010; Gehrels and Woodworth, 2013; Miller *et al.*, 2009; Mörner, 2004, 2012).

References

- Burton, D. 2013. SeaLevel.info—an independent analysis of NOAA’s long term sea-level records. <http://www.sealevel.info/html>, http://www.burtonsys.com/climate/MSL_global_trendtable1.html, http://www.sealevel.info/MSL_global_trendtable2.html.
- Gehrels, R. and Woodworth, P. 2013. When did modern rates of sea-level rise start? *Global and Planetary Change* **100**, 263–277.
- Goddard, S. 2013. NOAA tide gauges show 0.7 mm/year sea level rise. <http://stevengoddard.wordpress.com/2013/02/18/noaa-tide-gauges-show-0-7-mmyear-sea-level-rise/>.
- Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001. 3rd Assessment Report of the IPCC*.
- Miller, K.G., Sugarman, P.J., Browning, J.V., Horton, B.P., Stanley, A., Kahn, A., Uptegrove, J., and Aucott, M. 2009. Sea-level rise in New Jersey over the past 5000 years: implications to anthropogenic changes. *Global and Planetary Change* **66**: 10–18.
- Mörner, N.-A. 2004. Estimating future sea-level changes from past records. *Global and Planetary Change* **40** (1–2): 49–54.
- Mörner, N.-A. 2012. Sea level is not rising. *SPPI Reprint Series*.
- Pugh, D. 2004. *Changing sea-levels: Effects of tides, weather and climate*. Cambridge University Press, Cambridge.
- below.
- Cazenave *et al.* (2003) studied variation in global sea level on interannual to decadal time scales, focusing on the thermal expansion of the oceans and the continental water mass balance. They determined a rate of thermosteric sea-level rise over the previous 40 years of about 0.5 mm/year. They note, however, 1993–2000 analyses of TOPEX-Poseidon altimetry data and the global ocean temperature data of Levitus *et al.* (2000) both yielded rates of rise approximately six times greater than their inferred rate. They interpreted this to mean “an acceleration took place in the recent past, likely related to warming of the world ocean.” Other interpretations acknowledged by Cazenave *et al.* are that “the recent rise may just correspond to the rising branch of a decadal oscillation” and “satellite altimetry and in situ temperature data have their own uncertainties and it is still difficult to affirm with certainty that sea-level rise is indeed accelerating.” On this second point, Nerem and Mitchum (2001) indicate at least 20 years of satellite altimetry data are necessary to detect an acceleration in sea-level rise).
 - Jevrejeva *et al.* (2006) analyzed information in the Permanent Service for Mean Sea Level data-base using a method based on Monte Carlo Singular Spectrum Analysis, designed to remove 2- to 30-year quasi-periodic oscillations to derive nonlinear long-term trends for 12 large ocean regions. These curves were combined to produce the mean global sea level (upper) and rate-of-rise (lower) curves depicted in Figure 6.2.1.2.2. The figure shows no acceleration of sea-level rise since the end of the Little Ice Age around 1860. Jevrejeva *et al.* say “global sea-level rise is irregular and varies greatly over time” but “it is apparent that rates in the 1920–1945 period are likely to be as large as today’s.” In addition, they report their “global sea-level trend estimate of 2.4 ± 1.0 mm/year for the period from 1993 to 2000 matches the 2.6 ± 0.7 mm/year sea-level rise found [then] from TOPEX/Poseidon altimeter data.”
 - White *et al.* (2005) compared estimates of coastal and global averaged sea level for 1950 to 2000, confirming earlier findings of “no significant increase in the rate of sea-level rise during this 51-year period.” They note several earlier investigators (Douglas, 1991, 1992; Maul and Martin, 1993; Church *et al.*, 2004; Holgate and Woodworth, 2004) similarly concluded the measured rate of global sea-level rise was rather stable over the past hundred years, in contrast to the climate model projections for an increase in rate during the twentieth century.

Earlier Research

That global average sea level has been rising gently for the past 100+ years has been established by observation. The precise rates of change and the degree to which those rates vary through time remain open questions in the research literature. Some of the many papers that bear on the topic are summarized

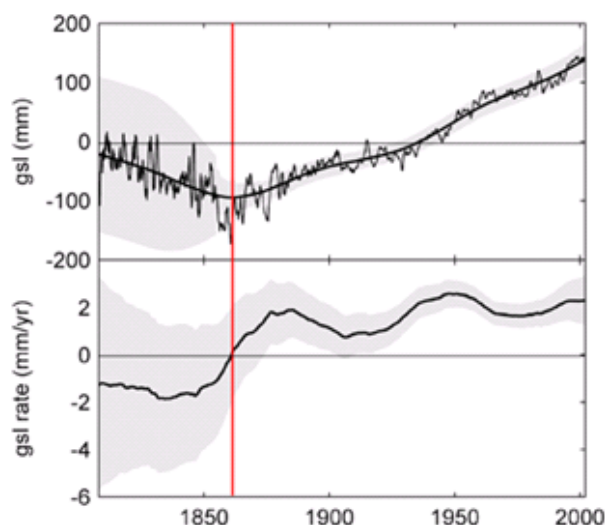


Figure 6.2.1.2.2. Mean global sea level (top), with shaded 95% confidence interval, and mean rate-of-rise (bottom), with shaded standard error interval. Adapted from Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S. 2006. Nonlinear trends and multiyear cycles in sea-level records. *Journal of Geophysical Research* **111**: C09012, doi:10.1029/2005JC003229, 2006.

- Aiming to improve the correction of tide gauge data for vertical substrate motion, Wöppelmann *et al.* (2009) analyzed GPS vertical velocities from a global network of 227 stations between 1997 and 2006. Of the stations they studied, 160 were located within 15 km of an established tide gauge. Assuming land motion is essentially linear over the time span considered, Wöppelmann *et al.* used the GPS vertical velocities they derived “to correct for the land motion affecting the tide gauge records to derive absolute (geocentric) changes in sea level.” They obtained a global-average rate of geocentric sea-level rise for the past century ranging from 1.55 to 1.61 mm/year, depending on whether one outlier (of 28 individual regions) was included or omitted from their analysis. Wöppelmann *et al.* conclude their result is “in good agreement with recent estimates” such as Church and White (2006; 1.7 mm/yr), Holgate (2007; 1.7 mm/yr), and Leuliette and Miller (2009; 1.5 mm/yr for 2003–2007, using satellite altimetry, Argo, and GRACE gravity observations to estimate the sum of the thermosteric and land ice contributions to sea-level rise).

- Wenzel and Schroter (2010) used a method of neural net analysis in a novel attempt to resolve problems such as tectonic movement or missing data at individual stations. Using 56 tidal stations with at

least 50 years of data each, the researchers first corrected the data for substrate movement up or down. The training data used for the neural net were three sets of altimetry data for recent decades, and all three results were shown. Wenzel and Schroter found no net trend in sea level for the South Atlantic and tropical Indian Oceans and a net decline for the Southern Indian Ocean. The Pacific Ocean showed an approximate 70-year oscillation in sea level that correlates (with lag) with the Pacific Decadal Oscillation, while the Atlantic showed cycles of 23 and 65 years. Overall, ocean basin changes showed lagged correlations with the PDO and Southern Annular Mode indices.

Averaging these results over the globe as a whole, Wenzel and Schroter arrived at a linear upward sea-level trend of 1.56 mm/year with no sign of recent acceleration. Their results agree with those of Hagedoorn *et al.* (2007) of 1.46 mm/year and Wöppelmann *et al.* (2009) of 1.61 mm/year, as well as other recent studies that give only slightly higher values, around 1.7–1.8 mm/year.

- In another novel approach, Church *et al.* (2011) compared results from tide gauge and satellite altimeter measurements. They based their approach on solving Earth’s sea-level and energy budgets together in a consistent manner, using the latest available data for the period 1972–2008. They found good agreement between the mean annual sea-level and energy budgets, as illustrated in Figure 6.2.1.2.3. They observed, “from 1972 to 2008, the observed sea-level rise [1.8 ± 0.2 mm/year from tide gauges alone and 2.1 ± 0.2 mm/year from a combination of tide gauges and altimeter observations] agrees well with the sum of energy budget contributions (1.8 ± 0.4 mm/year) in magnitude and with both having similar increases in the rate of rise during the period.”

Conclusions

These studies generally suggest the twentieth century has seen a steady rise in global sea level of between about 1.4 and 1.8 mm/yr, albeit modulated at a decadal or multidecadal scale.

This raises an obvious question: If the late twentieth century global warming was as extreme as the IPCC claims it has been, why can it not be detected in global sea-level data? The effects of the warming that led to the demise of the Little Ice Age—which the IPCC contends should have been considerably less dramatic than the warming of the late twentieth century—are readily apparent from the work of Jevrejeva *et al.* shown in Figure 6.2.1.2.2 above; they show a broad similarity in sea-level

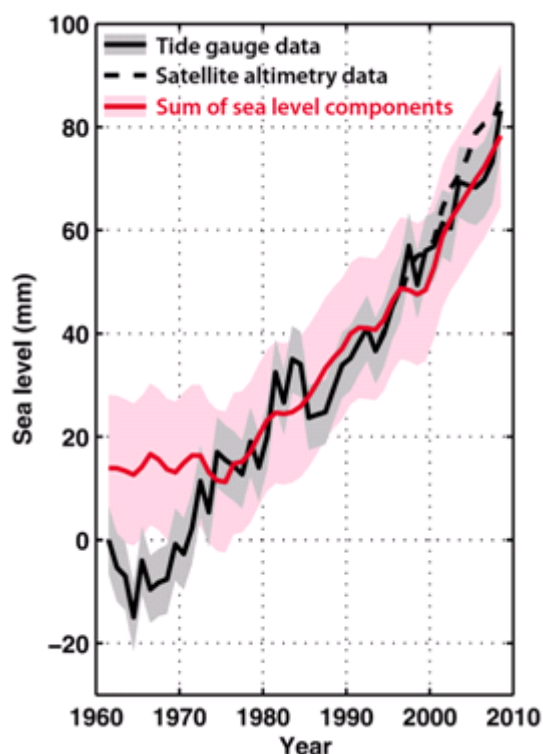


Figure 6.2.1.2.3. Mean global sea level vs. time, as derived from tide gauge data, satellite altimetry data and summing of the individual contributory components to sea level rise. Adapted from Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/2011GL048794.

response throughout the 150-year-long post-LIA period, with a lessening of the rate of rise for the 1960s through the 1980s.

Similarly, although the rate of increase in atmospheric carbon dioxide levels grew dramatically just after 1950, shifting from a 1900–1950 mean rate of rise of 0.33 ppm/year to a 1950–2000 mean rate of rise of 1.17 ppm/year, the mean global sea-level rate of rise did not trend smoothly upwards after 1950.

References

Cazenave, A., Cabanes, C., Dominh, K., Gennero, M.C., and Le Provost, C. 2003. Present-day sea level change: observations and causes. *Space Science Reviews* **108**: 131–144.

Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* **33**: 10.1029/2005GL024826.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950–2000 period. *Journal of Climate* **17**: 2609–2625.

Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/2011GL048794.

Douglas, B.C. 1991. Global sea level rise. *Journal of Geophysical Research* **96**: 6981–6992.

Douglas, B.C. 1992. Global sea level acceleration. *Journal of Geophysical Research* **97**: 12,699–12,706.

Holgate, S.J. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

Holgate, S.J. and Woodworth, P.L. 2004. Evidence for enhanced coastal sea-level rise during the 1990s. *Geophysical Research Letters* **31**: L07305, doi: 10.1029/2004GL019626.

Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S. 2006. Nonlinear trends and multiyear cycles in sea-level records. *Journal of Geophysical Research* **111**: C09012, doi:10.1029/2005JC003229, 2006.

Leuliette, E.W. and Miller, L. 2009. Closing the sea level rise budget with altimetry, Argo, and GRACE. *Geophysical Research Letters* **36**: 10.1029/2008GL036010.

Levitus, S., Antonov, J.L., Boyer, T.P., and Stephens, C.

2000. Warming of the world ocean. *Science* **287**: 2225–2229, doi:10.1126/science.287.

Maul, G.A. and Martin, D.M. 1993. Sea level rise at Key West, Florida, 1846–1992: America's longest instrument record? *Geophysical Research Letters* **20**: 1955–1958.

Nerem, R.S. and Mitchum, G.T. 2001. Sea level change. In: Fu, L.L. and Cazenave, A. (Eds.) *Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications*. Academic Press, San Diego, CA, pp. 329–349.

Wenzel, M. and Schroter, J. 2010. Reconstruction of regional mean sea level anomalies from tide gauges using neural networks. *Journal of Geophysical Research* **115**: 10.1029/2009JC005630.

White, N.J., Church, J.A., and Gregory, J.M. 2005. Coastal and global averaged sea level rise for 1950 to 2000. *Geophysical Research Letters* **32**: 10.1029/2004GL021391.

Wöppelmann, G., Letetrel, C., Santamaria, A., Bouin, M.-N., Collilieux, X., Altamimi, Z., Williams, S.D.P., and

Miguez, B.M. 2009. Rates of sea-level change over the past century in a geocentric reference frame. *Geophysical Research Letters* **36**: 10.1029/2009GL038720.

6.2.1.3. Satellites

Since the early 1990s, sea-level measurements have been made by microwave radar and laser ranging from various orbiting satellites, including the U.S. TOPEX-Poseidon, the European Remote-Sensing Satellite (ERS), Geosat Follow-On (GFO), EnviSat, and Jason series. Situated in polar geostationary orbit, these satellites are able to make repeat measurements of the exact distance to the sea surface at locations across the globe over cycles varying between three and 35 days as Earth rotates below the satellite (see Figure 6.2.1.3.1).

Thus, like tide gauge measurements although with almost complete coverage between 66° N and 66° S, satellites measure changing sea-level heights through time and therefore provide many records of sea-level change at different places (see Figure 6.2.1.3.2), which subsequently can be averaged into an estimate of global sea-level change over a specified period (Figure 6.2.1.3.3).

Averaging the repeat measurements for each location removes the effects of tides and waves. The nominal accuracy of about ± 100 mm can be improved to about ± 40 mm by averaging 10-day-separated repeat measurements, or ± 20 mm for monthly averages, at particular locations (Leuliette and Willis, 2011; Leuliette, 2012). This accuracy is not fully secure because we lack knowledge of the benchmark reference frame for the shape of Earth, the geoid, as well as other uncertainties introduced by the need for corrections for orbital drift and decay and for the stitching together of records from different successive satellites.

Both satellite and tide gauge data are used to estimate the rates of sea-level change over time by fitting a statistical model to the data, usually a linear model. The overall gradient of the resulting model fit is the estimate of the rate of sea-level change. There are complications with undertaking this type of analysis, including the errors associated with each data point and serial correlation of the measurements.

For time-series of sea-level data, successive measurements are often correlated with preceding data because there are repeating patterns, and as sea-level changes, the next measurement is more likely to change in the same direction than in the opposite direction. This increases the uncertainty in the estimates of the slope and is not always accounted

for. Further, the slope is usually quoted to a greater precision than the data (e.g., 0.1 mm for satellite data with an accuracy of about 20 mm), which can give a misleading impression of the accuracy of the estimated rate of sea-level rise.

It is important to note satellites and tide gauges do not measure quite the same thing. Tide gauges measure relative to a fixed land benchmark (usually the mean tide level), while satellites measure relative to a mathematical model of the shape of Earth's gravity field (geoid) that is not well characterized and varies over time. Accordingly, a component of satellite "sea-level change," perhaps as much as 50 percent, actually results from geoid changes.

Given these uncertainties, it is not surprising to find the satellite measurements yield an estimate of the rate of global sea-level change that differs from the tide gauge record, indicating an almost doubled rate of rise of more than 3mm/y. The main cause of this discrepancy is likely geoid inaccuracy (see Section 6.2.1.8 below).

Our discussion so far has centered on data collected and processed by NOAA's U.S.-based satellite fleet as presented at the NOAA Laboratory for Satellite Altimetry Web site (NOAA LSA, 2012) (Figure 6.2.1.3.3). But another problem with satellite-borne measurements is that significant differences occur among the sea-level curves reconstructed using different sensors and by different research groups.

For the period 2002–2012, independent sea-level measurements were conducted using the European Space Agency's (ESA) ENVISAT satellite. Until shortly before its failure in 2012, the 2004-onward ENVISAT record (Figure 6.2.1.3.4) persistently displayed a lower rate of sea-level rise than that indicated by U.S. measurements (Figure 6.2.1.2.3).

In June 2012, a new posting of an extended (back to 2002) ENVISAT sea-level curve was made (see Figure 6.2.1.3.5). For the new curve, corrections were made by reprocessing data and incorporating an unspecified "instrumental correction" of +2 mm/y. These corrections increased the "measured" ENVISAT rate of sea-level rise from 0.76 mm/y to 2.33 mm/y, bringing the ESA's results more in line with those of NOAA. Meanwhile, since early 2011, the NOAA data themselves had been adjusted toward a higher rate of sea-level rise by the addition of a +0.3 mm/y glacial isostatic (GIA) adjustment.

It is of course entirely possible the calibration and correction procedures used for any particular satellite instrument package are in error, and that later data adjustments are therefore justified when this is discovered—and perhaps especially so given that

Climate Change Reconsidered II

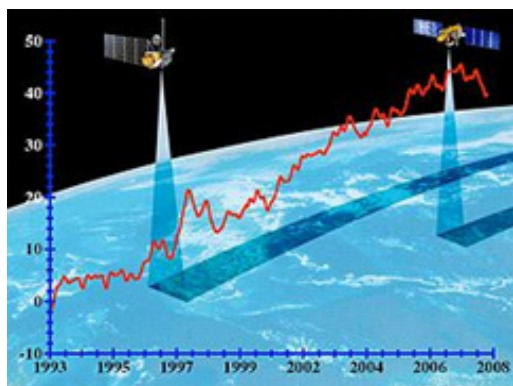


Figure 6.2.1.3.1. Graphic depicting NOAA satellite collecting sea-level data using radar altimetry, 1993–2008. Adapted from NASA.

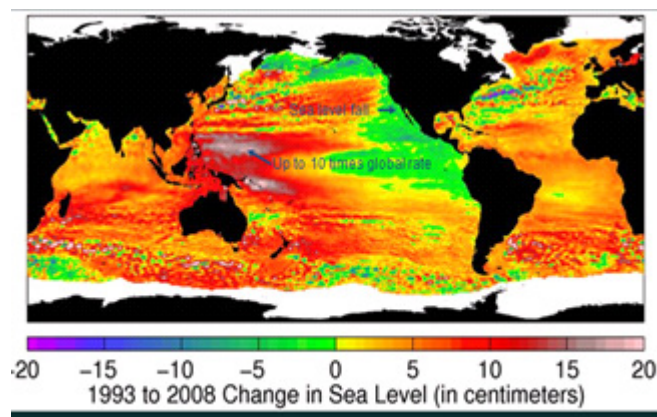


Figure 6.2.1.3.2. Sea-level rise is spatially very non-uniform. Synoptic global map of rate of sea-level change 1993-2008, as measured by radar altimetry. Adapted from NOAA.

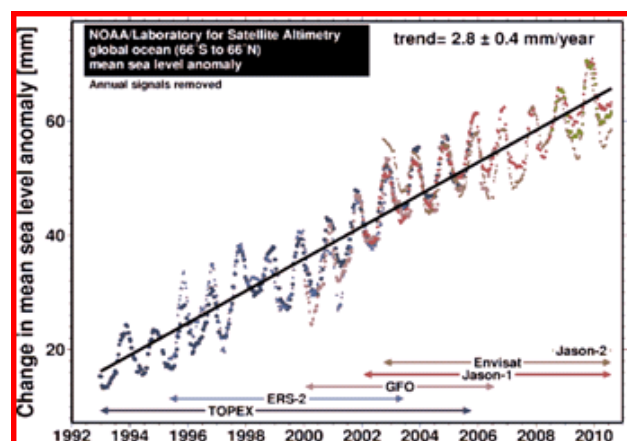


Figure 6.2.1.3.3. NOAA satellite altimetry, global sea-level change since 1992. Dataset composite, collected from successive satellites (coded in color) and plotted monthly.

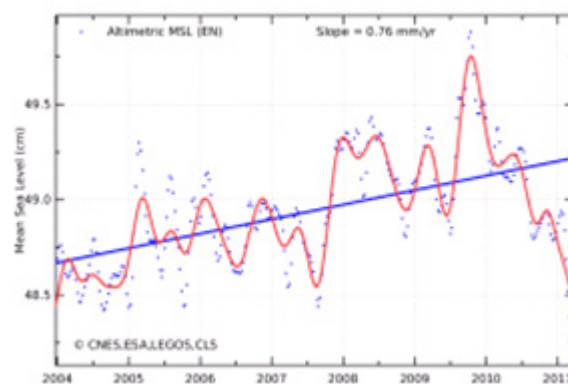


Figure 6.2.1.3.4. ENVISAT sea-level record with fitted trend line of +0.76 mm/y, 2002–2012. Adapted from Watts, A. 2012. ENVISAT's satellite failure launches mysteries. <http://wattsupwiththat.com/2012/04/12/envisats-satellite-failure-launches-mysteries/>.

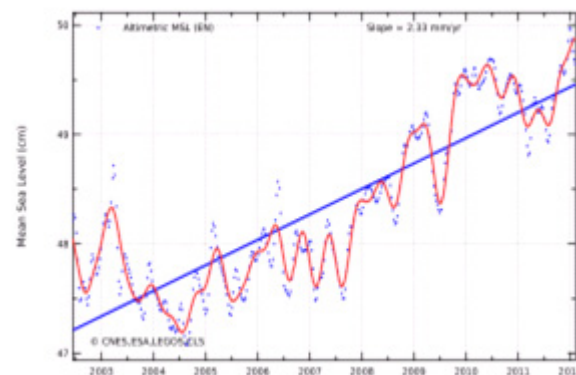


Figure 6.2.1.3.5. Arbitrarily adjusted ENVISAT sea-level record with fitted trend line of +2.33mm/y, 2004-2012 (after Watts, 2012).

ENVISAT persistently had been recording lower rates of rise than other satellites. But it is also disturbing that such adjustments nearly always seem to result in *increases* in the rate of sea-level rise determined; given a significant number of different arbitrary corrections, one might expect about one-half would increase and one-half lessen the rate of rise.

Government science agencies around the world often argue for “correction” of data to bring them into line with a preconceived result. New Zealand’s crown research agency, the National Institute of Water and Atmospheric Research (NIWA), has suggested all New Zealand tide gauge records should have a GIA adjustment of +0.4 mm/y to bring the regional Southwest Pacific rate of sea-level rise into line with the global estimate of 1.8 mm/y. This contradicts the

recommendation that sea-level rise should be assessed regionally and not in terms of a poorly constrained global average (Gehrels, 2010).

Conclusions

To the extent satellite altimetric measurements continue to return rates of sea-level rise greater than 2 mm/yr, and especially greater than 3 mm/yr, the results must remain suspect, because such high rates conflict with the well-established twentieth century rates of 1–2 mm/yr calculated from tide gauge data.

The mismatch between satellite and tide gauge records was addressed by Wunsch *et al.* (2007), who point out “the widely quoted altimetric global average values may well be correct, but the accuracies being inferred in the literature are not testable by existing in situ observations.” Using modeling, they derived an alternative global mean sea-level change estimate for 1993–2004 “of about 1.6 mm/y, or about 60% of the pure altimetric estimate, of which about 70% is from the addition of freshwater.” This rate of change is very close to that indicated by the tide gauge records.

References

Gehrels, R. 2010. Sea-level changes since the last glacial maximum: an appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science* **25** (1): 26–38. doi:10.1002/jqs.1273.

Leuliette, E., 2012. The budget of recent global sea-level rise 2005–2012. NOAA National Environmental Satellite, Data and Information Service.

Leuliette, E. and Willis, J., 2011: Balancing the sea-level budget. *Oceanography* **24** (2): 122–129. doi:10.5670/oceanog.2011.32.

NOAA LSA, 2012. Satellite altimeter Web page. <http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/index.php>

Watts, A. 2012. ENVISAT’s satellite failure launches mysteries. <http://wattsupwiththat.com/2012/04/12/envisat-satellite-failure-launches-mysteries/>.

Wunsch, C., Ponte, R.M., and Heimbach, P. 2007. Decadal trends in sea-level patterns: 1993–2004. *Journal of Climate* **20**(24): 5889–5911. doi: 10.1175/2007JCLI1840.1.

Earlier Research

The reconstruction of sea-level curves from satellite altimetric data remains a vigorous field of study. We summarize below three important earlier papers in the field.

- Church *et al.* (2004) used TOPEX/Poseidon

satellite altimeter data to estimate global empirical orthogonal functions, which they combined with historical tide gauge data to estimate monthly distributions of large-scale sea-level variability and change over the period 1950–2000. They estimated the globally averaged sea-level rise for the last half of the twentieth century at 1.8 ± 0.3 mm/year, a figure in close agreement with tide gauge estimates. In addition, they note “decadal variability in sea level is observed, but to date there is no detectable secular increase in the rate of sea-level rise over the period 1950–2000.” They conclude there was no increase in the rate of sea-level rise for the entire twentieth century, citing the work of Woodworth (1990) and Douglass (1992).

- Cazenave and Nerem (2004) seem to dismiss the caution shown by Cazenave *et al.* (2003) in claiming “the geocentric rate of global mean sea-level rise over the last decade (1993–2003) is now known to be very accurate, 2.8 ± 0.4 mm/year, as determined from TOPEX/Poseidon and Jason altimeter measurements.” Placing faith in this result leads them to note “this rate is significantly larger than the historical rate of sea-level change measured by tide gauges during the past decades (in the range of 1–2 mm/year).” Nonetheless, they concede “the altimetric rate could still be influenced by decadal variations of sea level unrelated to long-term climate change, such as the Pacific Decadal Oscillation, and thus a longer time series is needed to rule this out.”

Importantly, because it is often ignored, Cazenave and Nerem also note satellite altimetry reveals a “non-uniform geographical distribution of sea-level change, with some regions exhibiting trends about 10 times the global mean” (see Figure 6.2.1.3.2). Regional differences are also highlighted by the fact that “for the past 50 years, sea-level trends caused by change in ocean heat storage also show high regional variability.” Cazenave and Nerem report “these [satellite altimetric] tools seem to have raised more questions than they have answered.”

- Carton *et al.* (2005) note “recent altimeter observations indicate an increase in the rate of sea-level rise during the past decade to 3.2 mm/year, well above the centennial estimate of 1.5–2 mm/year,” noting further “this apparent increase could have resulted from enhanced melting of continental ice or from decadal changes in thermohaline and halosteric effects.” Using a new eddy-permitting Simple Ocean Data Assimilation version 1.2 reanalysis of global temperature, salinity, and sea level for the period 1968–2001, they determined “the effect on global sea-level rise of changing salinity is small except in

subpolar regions.” They also found warming-induced steric effects “are enough to explain much of the observed rate of increase in the rate of sea-level rise in the last decade of the twentieth century without need to invoke acceleration of melting of continental ice.”

It follows, as determined also by Lombard *et al.* (2005), that the high rate of global sea-level rise observed over the past decade is probably a transient result of the global ocean’s thermal behavior. Consequently, and in harmony with the findings of Levitus *et al.* (2005) and Volkov and van Aken (2005), there is no need to invoke the melting of land-based glacial ice to explain the observed recent increase in global sea level.

Conclusions

Estimates of sea-level change made using satellite-collected data remain problematic because, among other reasons, they are heavily dependent on the accuracy of a GIA adjustment that lacks independent verification (Houston and Dean, 2012). Summarizing comparisons between the tide gauge and satellite altimeter studies, Houston (2013) concludes, “[It] cannot be determined yet whether the greater trend measured by the altimeters and tide gauges from 1993 to 2011 is the leading edge of a sustained rise or a fluctuation similar to others that have occurred in the twentieth century.”

As Wunsch *et al.* (2007) noted:

At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology. The most urgent job would appear to be the accurate determination of the smallest temperature and salinity changes that can be determined with statistical significance, given the realities of both the observation base and modeling approximations. Both systematic and random errors are of concern, the former particularly, because of the changes in technology and sampling methods over the many decades, the latter from the very great spatial and temporal variability. It remains possible that the database is insufficient to compute mean sea-level trends with the accuracy necessary to discuss the impact of global warming—as disappointing as this conclusion may be. The priority has to be to make such calculations possible in the future.

Establishing the credibility of satellite-borne altimetric sea-level measurements awaits the launch of NASA’s new GRASP satellite or development of

some other mechanism whereby the accuracy of geoid models can be improved.

References

- Carton, J.A., Giese, B.S., and Grodsky, S.A. 2005. Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis. *Journal of Geophysical Research* **110**: 10.1029/2004JC002817.
- Cazenave, A., Cabanes, C., Dominh, K., Gennero, M.C., and Le Provost, C. 2003. Present-day sea level change: observations and causes. *Space Science Reviews* **108**: 131–144.
- Cazenave, A. and Nerem, R.S. 2004. Present-day sea level change: observations and causes. *Reviews of Geophysics* **42**: 10.1029/2003RG000139.
- Cazenave, A., Le Traon, P.-Y., and Ishii, M. 2005. Contribution of thermal expansion to present-day sea-level change revisited. *Global and Planetary Change* **47**: 1–16.
- Church, J.A., White, N.J., Coleman, R., Lambeck, K., and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950–2000 period. *Journal of Climate* **17**: 2609–2625.
- Douglas, B.C. 1992. Global sea level acceleration. *Journal of Geophysical Research* **97**: 12,699–12,706.
- Houston, J.R. 2013. Global sea level projections to 2100 using methodology of the Intergovernmental Panel on Climate Change. *Journal of Waterway, Port, Coastal, and Ocean Engineering* **139**: 82–87.
- Houston, J.R. and Dean, R.G., 2012. Comparisons at tide-gauge locations of glacial isostatic adjustment predictions with global positioning system measurements. *Journal of Coastal Research* **28**: 739–744.
- Levitus, S., Antonov, J.I., Boyer, T.P., Garcia, H.E., and Locarnini, R.A. 2005. EOF analysis of upper ocean heat content, 1956–2003. *Geophysical Research Letters* **32**: 10.1029/2005GL023606/.
- Lombard, A., Volkov, D.L., and van Aken, H.M. 2005. Climate-related change of sea level in the extratropical North Atlantic and North Pacific in 1993–2003. *Geophysical Research Letters* **32**: 10.1029/2005GL023097.
- Volkov, D.L. and van Aken, H.M. 2005. Climate-related change of sea level in the extratropical North Atlantic and North Pacific in 1993–2003. *Geophysical Research Letters* **32**: 10.1029/2005GL023097.
- Woodworth, P.L. 1990. A search for accelerations in records of European mean sea level. *International Journal of Climatology* **10**: 129–143.

Wunsch, C., Ponte, R.M., and Heimbach, P. 2007. Decadal Trends in Sea-level Patterns: 1993–2004. *Journal of Climate* **20**(24): 5889–5911. doi: 10.1175/2007JCLI1840.1

6.2.1.4. Short-term, decadal and multidecadal dynamic variability

Sea-level changes on a short-term, decadal, or multidecadal scale are driven by changes in the heat energy or dynamics of the ocean system (see, e.g., Figure 6.2.1.4.1; similar results were achieved by Fu *et al.*, 1987). These include the effects of spinning up or slowing down major current gyres and the effects of established climatic oscillations such as ENSO (El Niño-Southern Oscillation), the PDO (Pacific Decadal Oscillation), and the SAM (Southern Annular Mode). Sea-level change forced by such mechanisms is generally of low magnitude compared with geological time-scale changes (centimeters to a meter or two only) but can operate at rates as high as 5–10 mm/y.

Another important cause of shorter-term changes in sea level is fluctuation in the energy balance of the ocean, which leads to heating or cooling of the ocean;

i.e., thermosteric sea-level change. Fluctuations in sea level have been linked to sunspot cycles (Currie, 1976) and longer-term solar effects (van der Schrier *et al.*, 2002). After a phase of warming, expansion, and steric sea-level rise during the late twentieth century, ocean cooling has led to steric sea-level fall since 2002 (DiPuccio, 2009; Loehle, 2009).

Kolker and Hameed (2007) have shown short-term, non-tidal, local sea-level variability is much greater than the magnitude of long-term trends. The cause of this variability is partly unknown, but it includes the effects of storms, winds, floods, wind-driven Rossby waves,¹ shifts in major ocean currents, volcanic heating, and meteorological phenomena (ENSO, PDO).

References

- Currie, R.G. 1976. The spectrum of sea-level from 4 to 40 years. *Geophysical Journal of the Royal Astronomical Society* **46**(3): 513–520. doi:10.1111/j.1365-246X.1976.tb01245.x.
- Di Puccio, W. 2009. Have Changes in Ocean Heat Falsified the Global Warming Hypothesis? <http://pielkeclimatesci.wordpress.com/2009/05/05/have-changes-in-ocean-heat-falsified-the-global-warming-hypothesis-a-guest-weblog-by-william-dipuccio/>.
- Douglas, B.C., Cheney, R.E., and Agreen, R.W. 1983. Eddy energy of the Northwest Atlantic and Gulf of Mexico determined from GEOS 3 altimetry. *Journal of Geophysical Research: Oceans* **88**(C14): 9595–9603. doi:10.1029/JC088iC14p09595.
- Fu, L.-J., Vazquez, J., and Parke, M.E. 1987. Seasonal variability of the Gulf Stream from satellite altimetry. *Journal of Geophysical Research, Oceans* **92**: 749–754.
- Kolker, A.S. and S. Hameed. 2007. Meteorologically driven trends in sea-level rise. *Geophysical Research Letters* **34**: L23616, doi:10.1029/2007GL031814.
- Loehle, C. 2009. Cooling of the global ocean since 2003. *Energy and Environment* **20**: 101–104.
- van der Schrier, G., Weber, S.L., and Drijfhout, S.S., 2002. Sea-level changes in the North Atlantic by solar forcing and internal variability. *Climate Dynamics* **19**: 435–447

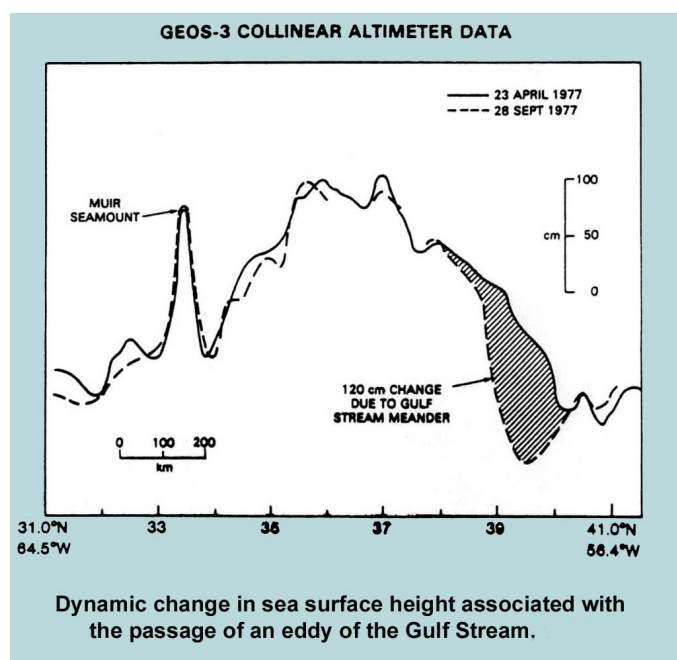


Figure 6.2.1.4.1. Dynamic changes in sea surface height associated with the passing of an eddy of the warm water Gulf Stream, 1977. Adapted from Douglas, B.C., Cheney, R.E., and Agreen, R.W. 1983. Eddy energy of the Northwest Atlantic and Gulf of Mexico determined from GEOS 3 altimetry. *Journal of Geophysical Research: Oceans* **88**(C14): 9595–9603. doi:10.1029/JC088iC14p09595.

¹ Oceanic Rossby waves travel from east to west under the influence of the shape and rotation of the Earth. They have dimensions of many hundreds of km horizontally but only displace the sea surface by a few cm. Nonetheless, Rossby waves transmit energy and redistribute momentum, thereby exerting effects on the intensity of ocean currents and affecting climate.

Earlier Research

Other papers that have identified short-term sea-level change signals include the following:

- Careful inspection of long historical tide gauge records identifies subtle decadal and multidecadal modulations on the twentieth century long-term rising trend (Marcos *et al.*, 2012). Twentieth century sea-level rise has imprinted on it a rhythmic pattern represented by successive periods of increasing and then decreasing rates of rise.
- In an analysis of high-quality tidal records selected worldwide, Holgate (2007) found a background average rate of sea-level rise of 1.6 mm/y (horizontal black line in Figure 6.2.1.4.2) with regular 20-year-long fluctuations of about -2 mm/y to +5 mm/y. Global sea level actually fell in the 1920s, 1940s, 1960s, 1980s, and around 2000.

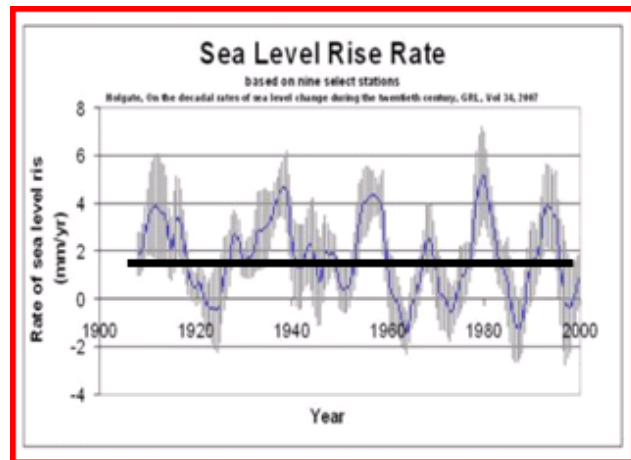


Figure 6.2.1.4.2. Rate of sea-level rise, 1910–2000, based upon analysis of high-quality tide gauge records. Note the average rate of rise (thick black line) of 1.6 mm/y. Note also the presence of fluctuations of rate of between about -2 and +5 mm/y on a decadal to multi-decadal scale, including periods of falling sea-level in 1920, 1940, 1960, 1980 and 2000. Adapted from Holgate, S. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* 34: 10.1029/2006GL028492.

- Zhang and Church (2012) made a detailed study of interannual and decadal variability in Pacific Ocean sea-level trends. Noting “on a regional scale, such a signal [of anthropogenic change] is mixed with that due to natural climate variability,” they set out to separate the natural and anthropogenic signals. This problem has become especially serious since the launch of the TOPEX/Poseidon altimeter, which has encouraged many researchers to report essentially

meaningless linear trends in sea-level rise over time spans ranging from a ridiculously short three years to a still-inadequate 18 years.

Zhang and Church used continuous near-global altimeter measurements since 1993 to attempt to separate interannual and decadal sea-level variability in the Pacific from the long-term background sea-level trend. Their results show “the decreasing regional sea level in the eastern equatorial Pacific is mainly associated with the Pacific Decadal Oscillation” and “for those island countries in the western tropical Pacific and especially low-lying atolls, the high rate of sea level rise over the altimeter era has a significant component associated with natural variability.” They conclude using altimeter-based trends as a reference for future climate change projections “needs to be treated with caution as regional sea level linear trends derived over the short altimeter era can be greatly affected by low-frequency climate variability.”

Conclusions

Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and dictate the ocean response to atmospheric pressure. For environmental management purposes, the dominance of these processes means sea-level changes should be assessed at local or regional scales, not globally.

The presence of decadal and multidecadal fluctuations does not change the general conclusion from tide gauge data that sea level has been rising by an average of about 1.7 mm/year over the twentieth century. However, the presence of these oscillations has a significant effect on the usefulness of linear sea-level trends determined from datasets shorter than the 60-year period of one PDO cycle. Unless such trends are corrected to take into account the position the data they are based on occupies in the longer-term cycle, they are of little value for either scientific or environmental management purposes.

The pitfall is especially great when shorter periods of time are used to infer an acceleration of sea-level rise has occurred (e.g., Merrifield *et al.*, 2009; Sallenger *et al.*, 2012), because that acceleration might be due entirely to the fortuitous position within the 60-year cycle of the data studied (Chambers *et al.*, 2012). Chambers *et al.* state, “one should be cautious about computations of acceleration in sea level records unless they are longer than two cycles of the oscillation.”

Natural decadal and multidecadal changes must be taken into account during any projection of future

sea levels, yet it is only very recently that scientists have begun to incorporate such changes into their sea-level models.

References

Chambers, D.P, Merrifield, M.A., and Nerem, R.S. 2012. Is there a 60-year oscillation in global mean sea level? *Geophysical Research Letters* **39**: 10.1029/2012GL052885.

Church, J.A. *et al.* 2010. Sea-level rise and variability: synthesis and outlook for the future. In: Church, J.A. *et al.* (Eds.) *Understanding Sea-Level Rise and Variability*. Wiley-Blackwell, Chichester, United Kingdom, pp. 402–419.

Church, J.A. and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* **32**: 585–602.

Feng, M., Li, Y., and Meyers, G. 2004. Multidecadal variations of Fremantle sea level: footprint of climate variability in the tropical Pacific. *Geophysical Research Letters* **31**: 10.1029/2004GL019947.

Holgate, S. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

Marcos, M., Tsimplis, M.N., and Calafat, F.M. (2012). Inter-annual and decadal sea-level variations in the North-western Pacific marginal seas. *Progress in Oceanography*: doi:10.1016/j.pocean.2012.04.010.

Merrifield, M.A., Merrifield, S.T., and Mitchum, G.T. 2009. An anomalous recent acceleration of global sea level rise. *Journal of Climate* **22**: 5772–5781.

Sallenger, A.H., Doran, K.S., and Howd, P.A. 2012. Hotspot of accelerated sea level rise on the Atlantic coast of North America. *Nature Climate Change*: 10.1038/NCLIMATE1597.

Zhang, X. and Church, J.A. 2012. Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters* **39**: 10.1029/2012GL053240.

6.2.1.5. Acceleration of sea-level rise

Rates of sea-level change are periodic on decadal and longer time scales. For that reason, linear regression though eustatic data is an unreliable technique with which to establish long-term sea-level trends for use in environmental management. Accurate portrayal of any long-term ocean-heating (steric) sea-level rise, putatively due to human influence, is possible only after short-term periodic sea-level behavior has been identified and the records adjusted to account for it.

The important question is not, “is the long-term sea level rising?” Geological, tide gauge, and satellite records all agree it is and, other things being equal, will continue to do so. Instead, to ascertain if rates of sea-level rise are increasing due to human influence we should ask “is sea-level rise accelerating?” The answer to that question is no.

The IPCC (2001) wrote “no significant acceleration in the rate of sea-level rise during the 20th century has been detected.” In 2007 it noted “global average sea-level rose at an average rate of 1.8 [1.3–2.3] mm per year over 1961 to 2003. The rate was faster over 1993–2003: about 3.1 [2.4–3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear.” This interpretation was based on a comparison of satellite altimetry data, which started in 1991, and tide gauge data. As discussed above (6.2.1.3), the satellite data estimate a higher rate of sea-level rise than do tide gauge data (Wunsch *et al.*, 2007), so this result is unsurprising and does not provide evidence of acceleration.

Subsequently, many authors have tested directly for accelerated rise using regional tide gauge datasets. For example, Hannah and Bell (2012) analyzed four 100-year long records from New Zealand’s four biggest ports (see Figure 6.2.1.5.1) and found no acceleration beyond the average linear rate of rise of 1.8 mm/yr.

Watson (2010) analyzed the three longest sea-level records (more than 100 years) available in Australasia, from Fremantle, Sydney, and Auckland. The average rates of sea-level rise exhibit by these sites since 1940 are 1.6, 0.4, and 1.2 mm/y, respectively, but all three sites show deceleration over the later parts of the twentieth century rather than acceleration (see Figure 6.2.1.5.2). Other authors also have provided evidence for a slowing rate of sea-level rise during the twentieth century, including Hannah (1990; 2004), Houston and Dean (2011, 2012), Boretti (2012a, b), and Gehrels *et al.* (2012). Woodworth *et al.* (2009) reviewed the available reconstructions for the twentieth century and concluded sea-level rise accelerated around 1920–1930 and decelerated around 1960.

Holgate and Woodworth (2004) derived a mean global, rather than regional, sea-level history using 177 coastal tide gauge records for 1955–1998. Extending that record back in time for another 50 years, Holgate (2007) analyzed nine long high-quality records from locations around the world (New York, Key West, San Diego, Balboa, Honolulu, Cascais, Newlyn, Trieste, and Auckland). The mean

sea-level curve for these locations over the 1955–1998 period was compared with the mean curve of the much larger set of 177 stations to establish whether the mean nine-station record would provide a

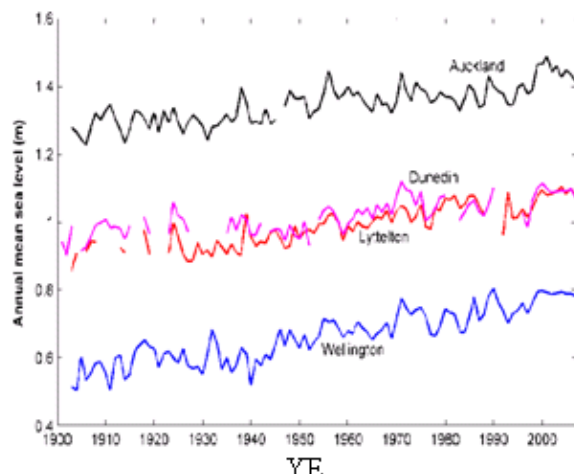


Figure 6.2.1.5.1. 100 year-long tide gauge records from four NZ ports (Auckland, Dunedin, Lyttelton and Wellington), showing a progressive, irregularly varying sea-level rise at an average background linear rate of 1.8 mm/yr. These rates of sea level change are similar to the world average rise as estimated from a global network of similar tide gauges. Adapted from Hannah, J. and Bell, R.G. 2012. Regional sea-level trends in New Zealand: *Journal of Geophysical Research* **117**: C01004–C01004.

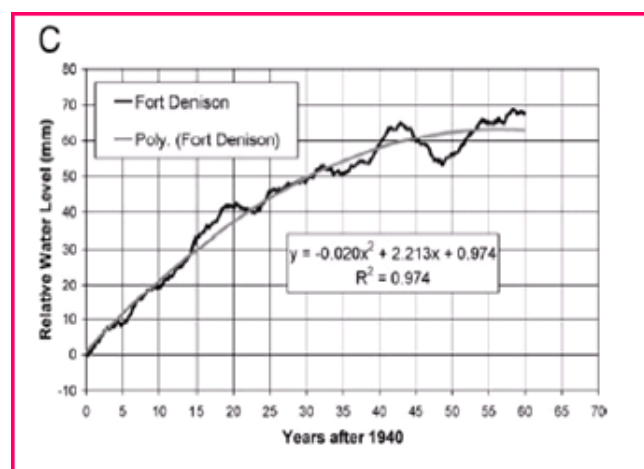


Figure 6.2.1.5.2. Sea-level curve for Sydney Harbour (Port Denison) since 1940, with fitted polynomial curve of decelerating nature. Adapted from Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea-level rise around mainland Australia? *Journal of Coastal Research* **27**: 368–377.

reasonable representation of global sea-level history for the longer period from 1904 to 2003. Holgate concluded, “a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to [do].”

Holgate thereby was able to provide a best-estimate representation of the 1904–2003 mean global sea-level history of the world. This, like Jevrejeva *et al.*’s (2006) similar reconstruction based on a larger tide gauge dataset, showed both multidecadal variations and an overall declining trend (see Figure 6.2.1.5.3). He calculated the mean rate of global sea-level rise was “larger in the early part of the last century (2.03 ± 0.35 mm/year 1904–1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954–2003).” In other words, global sea-level rise has been decelerating since the mid-twentieth century.

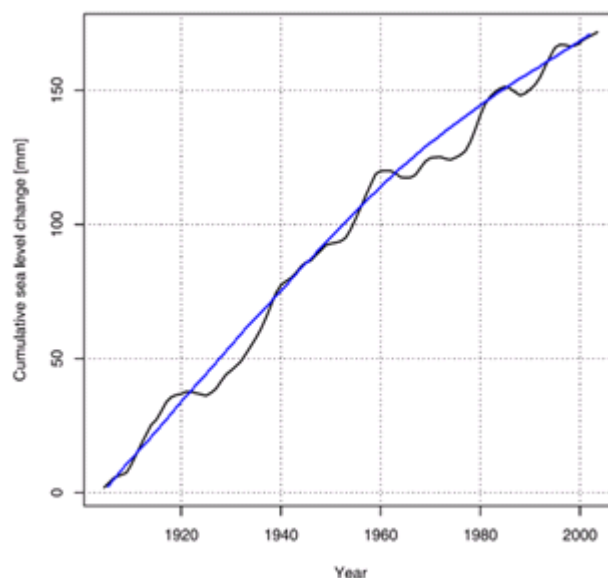


Figure 6.2.1.5.3. Cumulative increase in mean global sea level (1904–2003) derived from nine high-quality tide gauge records from around the world. Adapted from Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* **34**: L01602, doi: 10.1029/2006GL028492, 2007.

The only recent authors who claim to have detected recent acceleration in the rate of sea-level rise are Church and White (2006, 2011). Their earlier paper was based on merging short-term satellite altimetry with the long-term tide gauge records, a hazardous statistical exercise. The combined dataset was produced using a statistical model that matched

Observations: The Hydrosphere and Oceans

adjusted tide gauge data and satellite measurements during the period of overlap, and then used that match to reconstruct past sea levels in an attempt to correct for the sparse spatial distribution of older tide gauge data. Church and White (2011) identify acceleration of the long-term sea-level record around 1930 followed by a deceleration around 1960. They also depict the short-term sea-level rise rate was faster at the end of the twentieth century than the long-term rate.

Only broad summaries of the Church and White (2006, 2011) methodologies have been published and their results should be looked upon with caution. Comparison between the earliest version and most recent version of their work indicate pre-satellite sea-level data change as additional satellite data become available. This occurs because the statistical model underlying the merging is changing with the addition of further overlapping data (Church and White, 2011). Furthermore, break point and other statistical analyses indicate a significant change in the underlying characteristics of the data around 1992 (Chambers *et al.*, 2012), implying there was a fundamental change in sea-level processes then or the satellite data behave differently than the tide gauge data, as suggested by Wunsch *et al.* (2007) and Domingues *et al.* (2008). The presence of decadal and 60-year-long fluctuations in rates of sea-level change (Holgate, 2007; Chambers *et al.* 2011) and brevity of the satellite altimetric record (6.2.1.3, above) suggest it is too soon to use the satellite data as a reliable test for acceleration in late twentieth century sea-level rise.

References

- Chambers, D.P., Merrifield, M.A., and Nerem, R.S. 2012. Is there a 60-year oscillation in global mean sea-level? *Geophysical Research Letters* **39** (18): doi: 10.1029/2012GL052885.
- Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* **33**: L01602, doi:10.1029/2005GL024826.
- Church, J.A. and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* **32**: 585–602.
- Domingues, C.M., Church, J.A., White, N.J., Gleckler, P.J., Wijffels, S.E., Barker, P.M., and Dunn, J.R. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* **453** (7198) (June 19): 1090–1093. doi:10.1038/nature07080.
- Gehrels, R., Callard, S.L., Moss, P.T., Marshall, W.A., Blaauw, M., Hunter, J., Milton, J.A., and Garnett, M.H. 2012. Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. *Earth and Planetary Science Letters* **315/316**: 94–102.
- Hannah, J. 1990 Analysis of mean sea-level data from New Zealand for the period 1899–1988. *Journal of Geophysical Research* **95**: 12,399–12,405.
- Hannah, J. 2004. An updated analysis of long-term sea-level change in New Zealand: *Geophysical Research Letters* **31**: L03307, doi:10.1029/2003GL019166.
- Hannah, J. and Bell, R.G. 2012. Regional sea-level trends in New Zealand: *Journal of Geophysical Research* **117**: C01004–C01004.
- Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* **34**: L01602, doi: 10.1029/2006GL028492, 2007.
- Holgate, S.J. and Woodworth, P.L. 2004. Evidence for enhanced coastal sea-level rise during the 1990s. *Geophysical Research Letters* **31**: L07305, doi: 10.1029/2004GL019626.
- Houston, J.R. and Dean, R.G. 2011. Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research* **27**: 409–417.
- Houston, J.R. and Dean, R.G. 2012. Comparisons at tide-gauge locations of glacial isostatic adjustment predictions with global positioning system measurements. *Journal of Coastal Research* **28**(4): 739–744. doi:10.2112/JCOASTRES-D-11-00227.1.
- Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change*.
- Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S. 2006. Nonlinear trends and multiyear cycles in sea-level records. *Journal of Geophysical Research* **111**: C09012, doi:10.1029/2005JC003229.
- Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea-level rise around mainland Australia? *Journal of Coastal Research* **27**: 368–377.
- Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A., and Gehrels, W.R. 2009. Evidence for the accelerations of sea-level on multi-decade and century timescales. *International Journal of Climatology* **29**: 777–789.
- Wunsch, C., Ponte, R.M., and Heimbach, P. 2007. Decadal trends in sea-level patterns: 1993–2004. *Journal of Climate* **20**(24): 5889–5911, doi: 10.1175/2007JCLI1840.1.

Earlier Research

Several other recent papers bear on the question of an accelerated rate of sea-level rise and are briefly summarized below.

- Rahmstorf *et al.* (2012) compared Church and White (2006; 2011) and Jevrejeva *et al.* (2008) with three earlier reconstructions (Gornitz and Lebedeff 1987; Trupin and Wahr 1990; and Holgate and Woodworth 2004) of global sea level, finding general agreement among the analyses that sea-level rise began to accelerate in or before the nineteenth century (Jevrejeva, 2008), although there are very few tide gauge records extending back to the eighteenth century to better secure that result.

The reconstructions used different sets of tide gauges and different methodologies, including different corrections applied to the data. These corrections include adjustments for local data shifts and corrections for the inverse barometric effect² and seasonal effects. Most importantly, the isostatic (GIA) corrections have changed over time as successively newer models of crustal deformation have been calculated, in which regard Houston and Dean (2012) found the predicted GIA was poorly correlated with the GIA measured by continuous GPS, with no systematic pattern of deviations. It should not be surprising there are significant differences as well as similarities between the datasets, and those differences will affect the detection of long-term changes in the rate of sea-level rise.

- Boretti (2012a) analyzed data from the TOPEX and Jason series of satellite radar altimeters to test for recent changes in the rate of sea-level change. He reports the average rate of sea-level rise over the almost 20-year period of radar altimeter observations is 3.164 mm/yr (see Figure 6.2.1.5.4), which if held steady over a century would yield a mean global SLR of 31.64 cm, a little more than the low estimate for 2100 made by the IPCC. Boretti also finds that rather than accelerating, the rate of sea-level rise over the

measurement period is decelerating at a rate of -0.11637 mm/yr^2 and this deceleration is itself reducing at a rate of $-0.078792 \text{ mm/yr}^3$.

Boretti notes the deceleration of sea-level rise over the past ten years “is clearly the opposite of what is being predicted by the models,” especially as the reduction has been even more pronounced over the past five years. He further notes, “in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the sea level rise must be almost

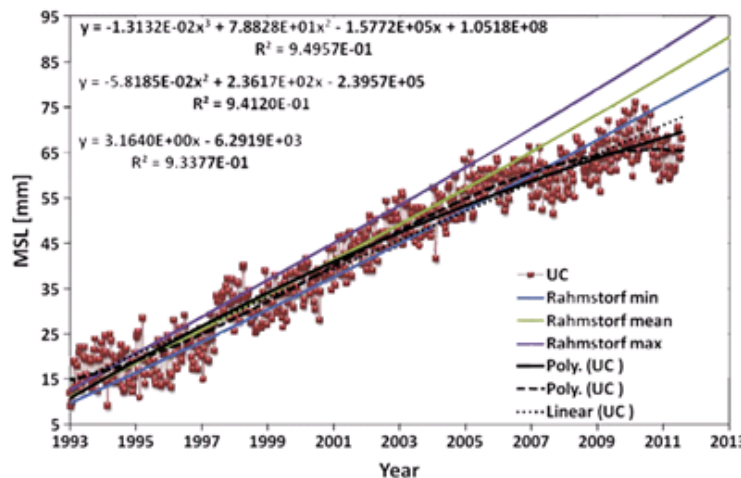


Figure 6.2.1.5.4. Comparison of MSL predictions from Rahmstorf (2007) with measurements from the TOPEX and Jason series. Boretti (2012a), who states in the figure caption that “the model predictions [of Rahmstorf, 2007] clearly do not agree with the experimental evidence in the short term.” Adapted from Boretti, A.A. 2012a. Short term comparison of climate model predictions and satellite altimeter measurements of sea levels. *Coastal Engineering* 60: 319–322.

11 mm/year every year for the next 89 years.” A rate of rise of 11 mm/yr has not been achieved once in the past 20 years; rates that fast have been experienced only during the full flush meltwater pulses during deglaciation. The average rise of 3.164 mm/yr found by Boretti is only 20 percent of the sea-level rise needed for the prediction of a one meter rise by 2100 to be correct.

- Boretti (2012b) reports the Australian government has said mass relocation of citizens will be required in the near future in response to “floods ... due to the rise of sea levels resulting from increased carbon dioxide emissions.” Government maps published for Sydney indicate 0.5, 0.8, and 1.1 meter rises in sea level. Boretti assesses the degree to which such alarm is justified and reports “the worldwide average tide gauge result obtained considering all the data included in the Permanent

² In the open ocean, sea level tends to rise/fall 10 mm for every 1 hPa decrease/increase in atmospheric pressure. Because there are interannual and longer fluctuations in mean pressure at sea level, sea level fluctuates in parallel in response.

Observations: The Hydrosphere and Oceans

Service for Mean Sea Level data base show a modest sea level rise and about zero acceleration.” He also notes “the Fort Denison, Sydney tide gauge result shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result.” Similarly, “the Fremantle tide gauge result, the only other tide gauge operational in Australia over more than a century, shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result and the result of Sydney.” Finally, he reports “the other tide gauges operational along the coastline of Australia over shorter time scales of 30 to 40 years on average also show the lack of any acceleration component in the rate of rise of sea levels.”

Summarizing his findings, Boretti concludes the “rise of sea level in the bay of Sydney by 2100 is therefore more likely less than the 50 mm measured so far over the last 100 years, rather than the meter [1000 mm] predicted by some models.”

- The Australian National Tidal Centre claimed 16 stations with 17 years of record showed a rate of sea-level rise of 5.4 mm/yr. Mörner and Parker (2013) reviewed the same records and found rates of sea-level rise average just 1.5 mm/yr, with no acceleration over recent years.

Conclusions

In its 2007 report, the IPCC projected global sea level was likely to rise somewhere between 18 and 59 cm by 2100. Since then, several model-based analyses have predicted much higher sea-level rise for the twenty-first century, even exceeding 1 meter in some cases (e.g., Rahmstorf, 2007; 2010).

In contrast, multiple careful analyses of tide gauge records by different research teams make it clear the acceleration of sea-level rise proposed by the IPCC and its scientists does not exist. Most records show either a steady state of rise or a deceleration during the twentieth century, both for individual records and for globally averaged datasets. In addition, and though only about 20 years long, the satellite radar altimeter dataset also records a recent decelerating rate of rise (Boretti, 2012a).

References

Boretti, A.A. 2012a. Short term comparison of climate model predictions and satellite altimeter measurements of sea levels. *Coastal Engineering* **60**: 319–322.

Boretti, A. 2012b. Is there any support in the long term tide gauge data to the claims that parts of Sydney will be

swamped by rising sea levels? *Coastal Engineering* **64**: 161–167.

Gornitz, V. and Lebedeff, S. 1987. Global sea-level changes during the past century. In; Nummedal, D., Pilkey, O.H., and Howard, J.D. (Eds.) *Sea-level Fluctuation and Coastal Evolution*, SEPM Special Publication No.41, The Society for Sedimentary Geology, Tulsa, Oklahoma, pp. 3–16.

Houston, J.R. and Dean, R.G. 2011. Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research* **27**: 409–417.

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis. Summary for Policy Makers. 4th Assessment Report of the Intergovernmental Panel on Climate Change.*

Jevrejeva, S., Moore, J.C., Grinsted, A., and Woodworth, P.L. 2008. Recent global sea-level acceleration started over 200 years ago? *Geophysical Research Letters* **35**: L08715–L08715.

Mörner, N-A. and Parker, A. 2013. Present-to-future sea level changes: The Australian case. *Environmental Science* **8**: 43–51.

Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* **315**: 368–370.

Rahmstorf, S. 2010. A new view on sea level rise: has the IPCC underestimated the risk of sea level rise. *Nature Reports Climate Change* **10**: 1038/climate.2010.29.

Rahmstorf, S. 2012. Sea-level rise: towards understanding local vulnerability. *Environmental Research Letters* **7**: 021001. doi: 10.1088/1748-9326/7/2/021001.

Trupin, A. and Wahr, J.M. 1990. Spectroscopic analysis of global tide gauge sea level data. *Geophysical Journal International* **100**(3): 441–453.

6.2.1.6. Atolls

The assertion that Pacific coral islands are being swamped or “drowned” by rising sea level, thus creating thousands of “climate refugees,” retains its hold over many environmentalists, although a London High Court judgment in 2007 against Al Gore found the claim to be untrue (Burton, 2007). Relentless media attention to the matter has ensured it remains in the public eye, with the Tuvalu Islands (Funafuti) receiving the most attention.

Charles Darwin was the originator of the modern theory of coral island and atoll formation (Darwin, 1842) (see Figure 6.2.1.6.1). He speculated when a new volcano erupts above sea level in the tropical

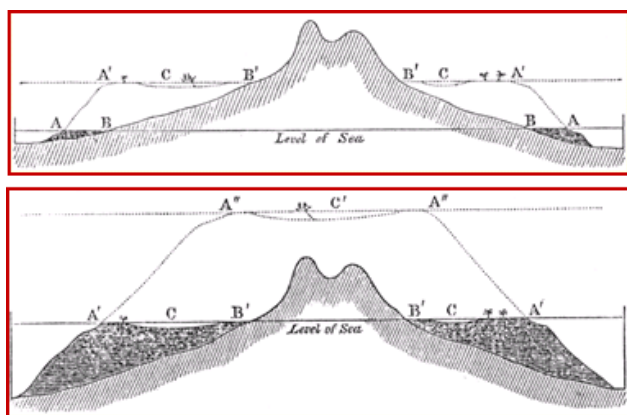


Figure 6.2.1.6.1. The formation of atolls by coral growth around a sinking volcanic island. Adapted from Darwin, C. 1842. *The Structure and Distribution of Coral Reefs*. London, Smith, Elder and Co.

ocean, corals colonize the shoreline, taking the form of fringing reefs. As the volcano cools and subsides, the reefs grow upwards and outwards, away from the volcanic island, keeping pace with the local sea-level rise caused by subsidence. A shallow-water lagoon forms between the island and the living reef, comprising an offshore, perimeter barrier reef. In the final stage of subsidence, the island itself disappears below sea level to leave a ring of coral reef that marks the location of the sunken volcano; thus are atolls born.

Seldom more than a meter or two above sea level, all atolls and related sand-cay and gravel-motu islands are at the continuing mercy of the wind, waves, tides, and weather events that built them. They are dynamic features of the seascape; over timescales of decades to centuries they erode here, grow there, and sometimes disappear beneath the waves forever. A coral atoll is not so much a “thing” as a process, and they are obviously not good places on which to develop major human population centers.

Because they are located so close to sea level, it is commonly assumed atolls or coral sand/gravel islands (cays or motu) are vulnerable to rising sea level. But investigations into the processes that govern the formation, evolution, and stability of cays and motu indicate they are very resilient to sea-level changes, provided human activities do not disrupt the natural processes, such as by constructing sea walls (Perry *et al.*, 2011). Formation of cays and motu requires sufficient sediment supply and sufficient wave energy acting on the reef surface to transport and deposit sediment. Perhaps counterintuitively, overwashing of the islands by storm waves, storm

surges, perigean tides, and tsunami is an important mechanism for increasing the elevation of the island by depositing new layers of sediment (Baines and McLean, 1976; Kench and Brander, 2006; Woodroffe, 2008; Etienne and Terry, 2012). When sea level rises, corals grow up to the higher sea level, normally easily keeping pace even at high rates of sea-level rise. When sea-level rise stops, the coral can grow only sideways.

Hence atolls are not a fixed “dipstick” with which to measure sea-level rise, as they are often treated: rather, a living coral reef forms part of a greater dynamic natural system. As Webb and Knetch (2010) write, “Typically, these [alarmist] studies treat islands as static landforms,” but “such approaches have not incorporated a full appreciation of the contemporary morphodynamics of landforms nor considered the style and magnitude of changes that may be expected in the future. Reef islands are dynamic landforms that are able to reorganize their sediment reservoir in response to changing boundary conditions (wind, waves and sea-level).” Coral growth, erosion, transport, and deposition of sediment and the prevailing oceanography and meteorology must be taken into account. The very fact that we have so many coral islands in the world, despite a rise in sea level of more than 100 m since the last ice age, shows coral islands are resilient—they don’t drown easily.

In essence, there appears to be an accommodation space, centered on mean sea level, that provides both the sediment and the energy needed to initiate and sustain coral cays and motu. Provided sea-level changes are slower than the rate at which the system can adjust the accommodation space, cays and motu are sustained. Rates of sea-level change for the foreseeable future are not high enough to threaten islands that are free to adjust in this way.

Connell (2003) found no evidence for the oft-repeated island doomsday claims about Tuvalu. Yamano *et al.* (2007) assessed 108 years of data for Fongafale Islet, Tuvalu, and found the problems attributed to sea-level rise in fact were due to population pressures resulting in the occupation of swamp land subject to periodic flooding throughout the historical record, thus demonstrating the great importance of real-world data—as opposed to climate model simulations—when it comes to considering the current and future status of Earth’s many low-lying islands. As Yamano *et al.* (2007) state, “examinations of global environmental issues should focus on characteristics specific to the region of interest. These characteristics should be specified using historical

reconstruction to understand and address the vulnerability of an area to global environmental changes.”

Webb and Kench (2010) found during the last part of the twentieth century 23 of the 27 Pacific atolls they studied remained unchanged or increased in area. They conclude, “The results show that island area has remained largely stable or increased over the time frame of analysis. Forty-three percent of islands increased in area by more than 3% with the largest increases of 30% on Betio (Tarawa atoll) and 28.3% on Funamanu (Funafuti atoll).” Over time, the island shapes changed in response to variations in dominant wave direction, and some islands migrated over their adjacent reef surfaces. A sensible management approach to this dynamic problem would be to design infrastructure so it can migrate with the evolving island, rather than attempt to maintain the island “frozen” in some arbitrary historical configuration.

In addition to the positive feedback loop of increased sediment supply demonstrated by Webb and Kench, the available evidence suggests the rate of long-term sea-level rise for most Pacific coral islands is less than the current global average rate of rise (see Figure 6.2.1.6.2). These records begin in 1993, when the Australian government set up a new series of accurate tide gauges to measure sea-level change on 14 tropical Pacific islands. At 19 years’ duration, even the longest of the records is too short to provide accurate long-term trend signals that might be associated with global warming. As the authors point out, “Caution must be exercised in interpreting the short-term trends—they will almost certainly change over the coming years as the dataset increases in length.”

No data exist to demonstrate an increasing, unusual, or unnatural rate of sea-level change for Pacific atolls, let alone any direct influence from increasing atmospheric carbon dioxide. As Meyssignac *et al.* (2012) conclude, “Results suggest that in the tropical Pacific, sea level trend fluctuations are dominated by the internal variability of the ocean-atmosphere coupled system. While our analysis cannot rule out any influence of anthropogenic forcing, it concludes that the latter effect in that particular region is still hardly detectable.”

Conclusion

The dynamic nature of an atoll is exacerbated, and its integrity jeopardized, when it is subjected to the environmental pressures created by a growing human population. Sand mining, construction project loading, and rapid groundwater withdrawal all cause

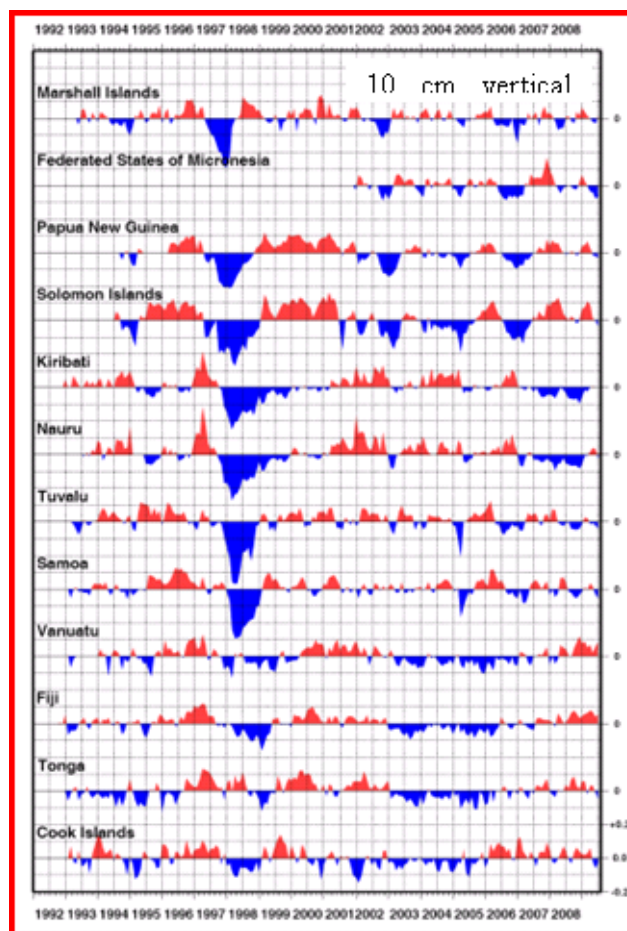


Figure 6.2.1.6.2. Relative sea-level variations since 1992, Pacific Island network. Australian Bureau of Meteorology, 2011. The South Pacific Sea-level and Climate Monitoring Program. Sea-level summary data report, July 2010–June 2010. http://www.bom.gov.au/ntc/IDO60102/IDO60102.2011_1.pdf.

local lowering of the ground surface, thereby encouraging marine incursion quite irrespective of any sea-level change. It is these processes in combination with episodic natural hazards such as tides and storms, not global sea-level change, that provide the alarming video footage of marine flooding on Pacific Islands that from time to time appears on our television news.

References

Australian Bureau of Meteorology, 2011. The South Pacific Sea-level and Climate Monitoring Program. Sea-level summary data report, July 2010–June 2010. http://www.bom.gov.au/ntc/IDO60102/IDO60102.2011_1.pdf.

Baines, G.B.K. and McLean, R.F. 1976. Sequential studies of hurricane deposit evolution at Funafuti atoll. *Marine Geology* **21**: M1–M8.

Burton, Justice Michael. 2007. Between Stuart Dimmock and Secretary of State for Education and Skills, in the High Court of Justice, Queen's Bench Division, Administrative Court—Judgement. <http://www.bailii.org/ew/cases/EWHC/Admin/2007/2288.html>.

Connell, J. 2003. Losing ground? Tuvalu, the greenhouse effect and the garbage can. *Asia Pacific Viewpoint* **44**: 89–107.

Darwin, C. 1842. *The Structure and Distribution of Coral Reefs*. London, Smith, Elder and Co.

Etienne, S. and Terry, J.P. 2012. Coral boulders, gravel tongues and sand sheets: features of coastal accretion and sediment nourishment by Cyclone Tomas (March 2010) on Taveuni Island, Fiji. *Geomorphology* **175–176**: 54–65.

Kench, P.S. and Brander, R.W. 2006. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. *Journal of Coastal Research* **22**(1): 209–223.

Meyssignac, B., Salas y Melia, D., Becker, M., Llovel, W., and Cazenave, A. 2012. Tropical Pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature? *Climate of the Past* **8**: 787802. doi: 10.5194/cp-8-787-2012.

Perry, C.T., Kench, P.S., Smithers, S.G., Riegl, B., Yamano, H., and O'Leary, M.J. 2011. Implications of Reef Ecosystem Change for the Stability and Maintenance of Coral Reef Islands. *Global Change Biology* **17**(12): 3679–3696. doi:10.1111/j.1365-2486.2011.02523.x.

Webb, A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change* **72** (2010): 234–246.

Woodroffe, C.D. 2008. Reef-island topography and the vulnerability of atolls to sea-level rise. *Global and Planetary Change*, **62**(1–2): 77–96.

Yamano, H., Kayanne, H., Yamaguchi, T., Kuwahara, Y., Yokoki, H., Shimazaki, H., and Chikamori, M. 2007. Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Global and Planetary Change* **57**: 407–416.

Earlier Research

Other recent papers on the effects of sea-level change on atolls or coral reefs are summarized below.

- Kench *et al.* (2005) proposed a new model for reef-island formation based on work conducted at the Maldives in the Indian Ocean. The model indicates

island formation starts below sea level with the accumulation of sand and gravel bars. Once these catch up with sea level and emerge, the calcareous sediment is stabilized by vegetation and lithification (beach rock formation). Subsequently the growth of the island is determined by the supply of sediment through overwashing processes.

- McCoy *et al.* (2010) examined the Mamanuca Islands, Fiji, and found that although the islands were younger than the Maldives, the same model was valid. They conclude “contemporary development of the reef islands in the Mamanuca’s and their links to sediment production on the reef flat suggests that they may be able to adjust their morphology to future environmental conditions.”

- In a study of Raine Island (11°35'28"S, 144°02'17"E), outer Great Barrier Reef (Australia), Dawson and Smithers (2010) employed historic survey maps, topographic survey datasets of earlier researchers, and modern digital elevation data to reconstruct a 40-year (1967–2007) shoreline history of the island. Their analyses demonstrated Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007, and overall Raine Island underwent a net accretion of $68,400 \pm 6,700 \text{ m}^3$ during that time. Dawson and Smithers conclude “future management strategies of Raine Island and other islands of the Great Barrier Reef should recognize that perceptions of reef island erosion can arise from large short-term seasonal and storm-derived sediment redistribution from one part of the island to another or to a temporary storage on the adjacent reef flat” but these phenomena do not necessarily lead to “a net permanent loss from the island sediment budget.”

- Rankey (2011) based his integrated study of 17 islands on the Maiana and Aranuka atolls of Kiribati’s Gilbert Island chain on integrated field observations, differential global positioning system data, historical aerial photographs, and ultrahigh-resolution remote sensing images. Examining the nature, spatial patterns, and rates of change of the shorelines of the islands he studied, Rankey found short-term (four-year) rates of shoreline change can indeed be dramatic, with significant intrusion of seawater over shallowly sloping shores. Over longer (40-year) periods the rates of change are much smaller and result in both slightly larger (growing) and slightly smaller (shrinking) islands. Rankey concludes “the atoll islands are not washing away” and counsels “solutions must consider the natural complexity of these [island] systems, rather than advocate overly

Observations: The Hydrosphere and Oceans

simplistic notions of the causes of, and the solutions to, coastal change.”

- Ford (2012) reported on the shoreline status of Majuro Atoll, the capital and most populated atoll in the Republic of the Marshall Islands. He used a combination of aerial photos and satellite imagery to analyze shoreline change of the island over the past three-and-a-half decades, a period characterized by rapidly increasing population, coastal development, and a rising sea level on the order of 3 mm/year. Although the rural lagoon shore of Majuro Atoll has been predominantly eroding, Ford found, the ocean-facing shore has been largely accreting, and at a much faster rate. Within the urban area of Majuro he finds shoreline change “has been largely driven by widespread reclamation for a mix of residential, commercial and industrial activities.” Thus, “despite a rising sea level ... the landmass of Majuro has persisted and, largely because of reclamation, increased in size.” Ford notes demands are placed on the limited land available as an atoll population increases, but for Majuro Atoll “it is likely that land reclamation will continue to satisfy this demand.” He adds, “the notion that sea level rise is a singular driver of shoreline change along atolls is spurious,” and “adopting such a notion is an impediment to the sustainable management of coastal resources within urban atolls.”

- Dunne *et al.* (2012) studied rising sea levels around the shorelines of the Chagos Archipelago (which includes the Diego Garcia Atoll), Indian Ocean. Sheppard and Spalding (2003) had reported a tide gauge situated on Diego Garcia indicated a local sea-level rise of 5.44 mm/year for 1988–1999. Just three years later, another analysis of the same gauge for the slightly longer period 1988–2000 had reported a lesser rate of 4.35 mm/year (Ragoonaden, 2006). In Dunne *et al.*’s view both of these analyses “were based only on short tide-gauge datasets, involved inappropriate statistical methods, and as a result have given an erroneous impression of the magnitude and significance of sea-level rise in this area.”

Dunne *et al.* used tide gauge and satellite altimeter records and ocean models and found “no evidence of any statistically significant sea-level rise either from the Diego Garcia tide gauge (1988–2000 and 2003–2011) or in the satellite altimetry record (1993–2011).” In addition, they note the lack of evidence for subsidence in the islands, consistent with GPS observations that Diego Garcia uplifted by 0.63 ± 0.28 mm/year between 1996 and 2009. Dunne *et al.* conclude, “collectively these results suggest that this has been a relatively stable physical environment, and

that these low-lying coral islands should continue to be able to support human habitation, as they have done for much of the last 200 years.”

Conclusions

On October 17, 2009, members of the Maldives’ Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to the very existence of their country’s nearly 1,200 coral islands. While underwater, they signed a document calling on all nations to reduce carbon (sic) emissions in response to the carbon dioxide threat.

The papers summarized above make it clear that observational and field evidence from a wide geographic range of low-lying ocean islands directly contradicts this theoretical threat.

Studies such as those by Webb and Kench (2010) and Dawson and Smithers (2010) have enabled a much better understanding of the likely effects of sea-level rise, should it happen, on low-lying islands. These effects include an increasing accommodation space for new coral reef growth and (bioclastic) sediment; reinvigoration of carbonate production on reef flats where further vertical reef growth today is inhibited by a stable or falling sea level; and an increase in the efficiency of waves to transport and accrete new and stored sediment to an island depocentre. The views of the Maldives Cabinet and its supporters notwithstanding, a rise in sea level on coral shorelines will most likely lead to an expansion of reef area and associated sediment banks. As Webb and Kench concluded, in contradiction of “widespread perceptions that all reef islands are eroding in response to recent sea level rise, ... reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20–60 years.”

References

- Dawson, J.L. and Smithers, S.G. 2010. Shoreline and beach volume change between 1967 and 2007 at Raine Island, Great Barrier Reef, Australia. *Global and Planetary Change* **72**: 141–154.
- Dunne, R.P., Barbosa, S.M., and Woodworth, P.L. 2012. Contemporary sea level in the Chagos Archipelago, central Indian Ocean. *Global and Planetary Change* **82–83**: 25–37.
- Ford, M. 2012. Shoreline changes on an urban atoll in the central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research* **28**: 11–22.

Kench, P.S., McLean, R.F., and Nichol, S.L. 2005. New model of reef-island evolution: Maldives, Indian Ocean. *Geology* **33**(2): 145–148. 10.1130/G21066.1

McCoy, H., Kennedy, D.M., and Kench, P.S. 2010. Sand cay evolution on reef platforms, Mamanuca Islands, Fiji. *Marine Geology* **269**: 61–73. 10.1016/j.margeo.2009.12.006

Ragoonaden, S. 2006. Sea level activities and changes on the islands of the western Indian Ocean. *Journal of Marine Science* **5**: 179–194.

Rankey, E.C. 2011. Nature and stability of atoll island shorelines: Gilbert Island chain, Kiribaati, Equatorial Pacific. *Sedimentology* ([0-9])(e)(:): 1831–1859.

Sheppard, C.R.C. and Spalding, M. 2003. *Chagos Conservation Management Plan*. British Indian Ocean Territory Administration. Foreign and Commonwealth Office, London, United Kingdom.

6.2.1.7. Other sea-level studies

We summarize in this section three recent sea-level studies that are not easily categorized.

- Woppelmann *et al.* (2008) examined “the issue of a possible tide gauge datum discontinuity for Brest ... caused by the bombing of the city in August 1944,” using historical leveling information and a comparison of sea-level data between adjacent stations. The Brest tide gauge was found to be “‘stable’ over the 1889–1996 period” because of the development of “an accurate datum connection between recently rediscovered 18th century sea level data (back to 1711) and those of the present day.” An “interesting by-product” of their analysis was the close match that emerged between the Brest record and two long tide records in the U.K. at Liverpool and Newlyn. The three records show a roughly coincident increase in the rate of relative sea-level rise around the end of the nineteenth century, after which all three datasets define similar linear increases with time through to 2007.

If one splits the period of linear sea-level rise determined for Brest into two equal 57-year parts centered on the middle of the twentieth century—1893 to 1950 and 1950 to 2007—the two parts can be compared with an atmospheric CO₂ concentration that rose about 3.8 times faster over the second period than it did over the first. Since mean sea level rose at a constant rate over the entire 114 years, it is unlikely the historical increase in atmospheric CO₂ controlled the steady sea-level rise.

- Langley *et al.* (2009) studied the effect of rising

sea level on coastal wetlands in the eastern United States with respect to plant growth and CO₂ concentration. In the microtidal Kirkpatrick Marsh of Chesapeake Bay, each of several 200m² plots was outfitted with a surface elevation table (SET) to measure soil elevation change. Langley *et al.* then exposed half the plots to an extra 340 ppm of CO₂ for two years, while “data from a greenhouse mesocosm experiment (Cherry *et al.*, 2009) were used to examine how elevated CO₂ might affect elevation response under simulated sea level rise scenarios.”

The researchers found the plots with extra CO₂ increased fine root productivity by an average of 36 percent over the two-year study, and aboveground biomass production was increased by as much as 30 percent. These results were consistent with a 20-year record of elevated CO₂ treatment in a previous study on the same marsh by Erickson *et al.* (2007). The elevated CO₂ also caused an increase in root zone thickness of 4.9 mm/year compared with only 0.7 mm/year in the ambient CO₂ treatment, resulting in “a slight loss of elevation in ambient CO₂ (-0.9 mm/year) compared with an elevation gain (3.0 mm/year) in the elevated CO₂ treatment.” Furthermore, Cherry *et al.* (2009) have determined from another greenhouse mesocosm experiment that “the CO₂ effect was enhanced under salinity and flooding conditions likely to accompany future sea level rise.”

Langley *et al.* conclude, “by stimulating biogenic contributions to marsh elevation, increases in the greenhouse gas, CO₂, may paradoxically aid some coastal wetlands in counterbalancing rising seas.” They note this finding bears “particular importance given the threat of accelerating SLR to coastal wetlands worldwide,” such as the recent Environmental Protection Agency report of Reed *et al.* (2008), which suggested “a 2-mm increase in the rate of SLR will threaten or eliminate a large portion of mid-Atlantic marshes.” Langley *et al.*’s research suggests the growth-promoting effect of atmospheric CO₂ enrichment will more than compensate for its hypothetical sea-level-raising effect.

- Albrecht *et al.* (2011) developed an index time series for changes in regional mean sea-level (RMSL) changes in the German Bight, North Sea. They employed two approaches—one that uses arithmetic means based on all available data for each time step, and another that uses empirical orthogonal functions. For comparison of their results with global mean sea-level data they used the 15 tide gauge dataset for 1843–2008 described and provided by Wahl *et al.* (2010, 2011).

Albrecht *et al.* report both methods produce similar results for the time period 1924–2008. Regional mean sea level increased at rates between 1.64 and 1.74 mm/year with a 90% confidence range of 0.28 mm/year in each case. Regarding possible acceleration in RMSL rise within the past few decades, they note in terms of 20-year trends, the most recent rates are “relatively high ... but not unusual and ... similar rates could also be identified earlier in the record.” Albrecht *et al.* reaffirm in the conclusion of their paper that “present rates of RMSL rise in the German Bight are relatively high, but are not unusual in the context of historical changes.” Similar conclusions regarding recent acceleration were drawn by Haigh *et al.* (2009) for the North Sea region of the English Channel.

References

Albrecht, F., Wahl, T., Jensen, J., and Weisse, R. 2011. Determining sea level change in the German Bight. *Ocean Dynamics* **61**: 2037–2050.

Cherry, J.A., Ward, A.K., and Ward, G.M. 2009. The dynamic nature of land-water interfaces: changes in structure and productivity along a water depth gradient in the Talladega Wetland Ecosystem. *Verhandlungen International Vereinigung Limnologie* **30**(6): 977–980.

Erickson, J.E., Megonigal, J.P., Peresta, G., and Drake, B.G. 2007. Salinity and sea level mediate elevated CO₂ effects on C₃–C₄ plant interactions and tissue nitrogen in a Chesapeake Bay tidal wetland. *Global Change Biology* **13**: 202–215.

Haigh, I., Nicholls, R., and Well, N. 2009. Mean sea level trends around the English Channel over the 20th century and their wider context. *Continental Shelf Research* **29**: 2083–2098.

Langley, J.A., McKee, K.L., Cahoon, D.R., Cherry, J.A., and Megonigal, J.P. 2009. Elevated CO₂ stimulates marsh elevation gain, counterbalancing sea-level rise. *Proceedings of the National Academy of Sciences* **106**(15): 6182–6186. 10.1073/pnas.0807695106.

Reed, D.J., Bishara, D.A., Cahoon, D.R., Donnelly, J., Kearney, M., Kolker, A.S., Leonard, L.L., Orson, R.A., and Stevenson, J.C. 2008. Site-specific scenarios for wetlands accretion as sea level rises in the Mid-Atlantic Region. Section 2.1 in: *Background Documents Supporting Climate Change Science Program*

Synthesis and Assessment Product 4.1.

Wahl, T., Jensen, J., and Frank, T. 2010. On analyzing sea level rise in the German Bight since 1884. *Natural Hazards and Earth System Sciences* **10**: 171–179.

Wahl, T., Jensen, J., Frank, T., and Haigh, I.D. 2011. Improved estimates of mean sea level changes in the German Bight over the last 166 years. *Ocean Dynamics* **61**: 701–715.

Woppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., and Woodworth, P. 2008 Tide gauge datum continuity at Brest since 1711: France’s longest sea-level record. *Geophysical Research Letters* **35**: L22605/.

6.2.1.8. Isostasy, GRACE

6.2.1.8.1 Isostasy

The reconstructed post-glacial sea-level curve of Figure 6.2.1.8.1.1 attempts to portray the true eustatic sea-level history of the past 20,000 years. To a first approximation, it is a history of the increasing volume of water in the world ocean caused by glacial melting and the steric expansion of a warming ocean. However, the measurements that underpin curves like this are made with respect to particular local relative sea levels at specific coastal locations and are affected by the movement up or down of the local geological substrate as well as by the notional global sea level.

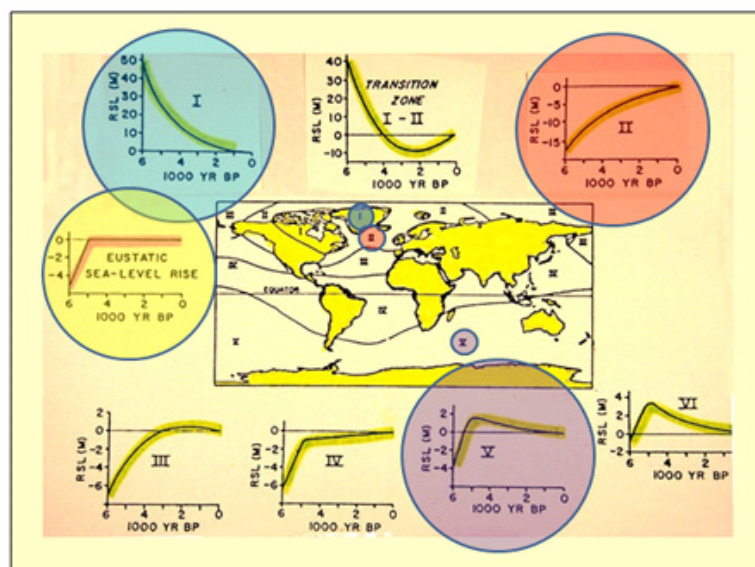


Figure 6.2.1.8.1.1. Local relative sea-level curves for the past 6,000 years, modeled to include hydro-isostatic effects combined with an idealized eustatic curve. Adapted from Clark, J.A. and Lingle, C.S. 1979. Predicted relative sea-level changes (18,000 Years B.P. to present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research* **11**: 279–298.

As the ice melted after the last glaciation, the increasing volume of the ocean caused two important changes to occur in the surface loading of Earth. First, the removal of an ice cap causes the formerly depressed (by loading) crust beneath to rebound upward by glacio-isostasy. Over 10,000 years during the Holocene, this rebound attained a magnitude of more than 100 meters at locations beneath the center of the former Scandinavian icecap, which are therefore characterized by falling post-glacial sea levels.

Second, an increasing ocean volume causes sea level to rise and the shoreline to transgress across the edges of the continental platforms, turning former glacial coastal plains into today's shallowly submergent continental shelf. The extra ocean water above the flooded continental shelf has the form of a coastline-parallel, landward-tapering prism, which provides a new crustal load that subsequently causes gentle hydro-isostatic uplift in the vicinity of the shoreline and hydro-isostatic sinking offshore, in both cases with a magnitude up to a few meters.

Overall, the effect is one of a seaward tilting of the crust beneath the continental shelf, with the rotational axis of tilting located near the sea-level high-stand shoreline (Chappell *et al.*, 1983; Tamisiea and Mitrovica, 2011).

In a classic 1979 paper, Clark and Lingle provided a modeled analysis of the way in which these isostatic effects combine with an assumed eustatic sea-level curve (see Figure 6.2.1.8.1.1, yellow circle) to produce a variety of local sea-level responses over the past 6,000 years that can be organized into recognizable geographic zones.

In proximal locations beneath former icecaps such as Greenland (blue circle; Zone I), strong glacio-isostatic rebound produces a falling relative sea-level. In far-field locations such as Australia and New Zealand (purple circle; Zone V), a shoreline overshoot of 2–4 meters at the end of the eustatic rise is followed by gradual relative sea-level fall in response to gentle hydro-isostatic deformation. And in intermediate locations such as the margins of the North Atlantic Ocean (red circle; Zone II), situated on the periphery of ice-sheet loading influence, interaction of these and other factors results in a relative sea-level curve that rises asymptotically to the present shoreline.

Isostatic uplift at a rate of, say, 2 mm/y (20 cm/century) may not sound like much on human generational time scales, but if the change is negative

(land sinking) it is enough to more than double the “best estimate” 18 cm/century rate of global sea-level rise over the twentieth century. Conversely, if the change is positive (land rising), it is enough to convert that same eustatic rise into a falling rate of 2 cm/century. Obviously, and as Clark and Lingle were among the first to model, over geological timescales of millennia even small rates of isostatic depression or rebound can have a significant effect on the physiography of the shoreline and its position relative to local sea level.

The effect of these isostatic effects is displayed in Figure 6.2.1.8.1.2, which is a plot of the present-day elevations of more than 4,000 worldwide radiocarbon-dated shorelines of post-glacial age. Predictably, the pattern displayed is one of increasing elevation of particular shorelines above or below sea level with increasing time elapsed (i.e., from left to right across the figure), the sign of any plotted point indicating whether the sampled site is in an area of uplift or sinking. Accordingly, sites situated around sea level at 10,000 y BP (early Holocene) now occupy a range of elevations between about -100 m

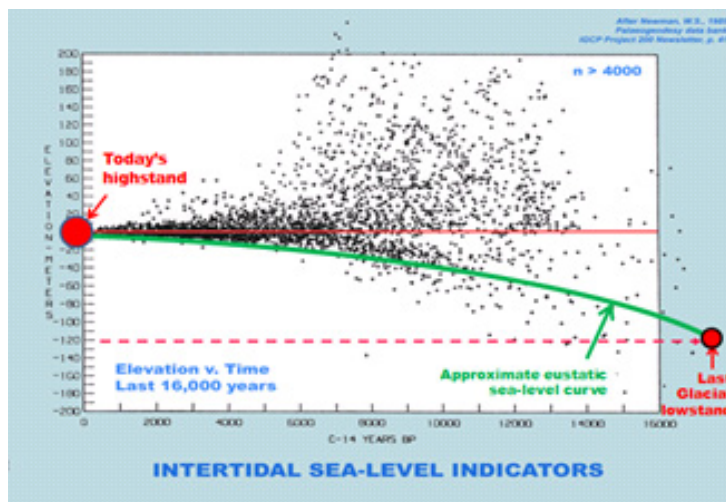


Figure 6.2.1.8.1.2. Worldwide plot of shoreline elevations with ages between 16,000 yBP and today. Adapted from Pirazzoli, P.A., Grant, D.R., and Woodworth, P. 1989. Trends of relative sea-level change: past, present and future. *Quaternary International* 2: 63–71. doi:10.1016/1040-6182(89)90022-0.

and +150 m, which indicates subsidence and uplift rates of up to -10 mm/y and +15 mm/y, respectively.

The large changes in ground level caused by glacio- and hydro-isostasy in the short period since the last glaciation serve as a warning regarding the naïve application of paleo-sea-level data from the previous interglacial, about 125,000 years ago. Sea-

Observations: The Hydrosphere and Oceans

level indicators from the last interglacial also may be distorted by differing regional isostatic responses, but over about 100,000 rather than 15,000 years. It is thus inadvisable to use such data as predictors of future maximum sea levels during the present interglacial (Holocene and Recent).

The difficulty arises not only because of GIA variability in time and space, but also from longer-term uplift or depression in different tectonic provinces. Means of separating the sea-level and tectonic influences have been devised (Chappell, 1974), but they rely on assumptions of a fixed sea-level point in time. Even in locations thought to be unaffected by major crustal uplift or depression, geochronological ages suggest successive sea levels reached much the same elevation (van Vliet Lanoe *et al.*, 2000). Claims of a last interglacial sea level of between +6.6 and +9.4 m from a probabilistic analysis along allegedly stable coastline areas (Kopp *et al.*, 2009) contain circular arguments. In any event, what constitutes a stable region and how can such stability be shown? In addition, other crustal influences are usually ignored; Menard (1971) provided a map of oceanic crust, created since the last interglacial at mid-ocean ridge, that would have displaced sea level. The similar effects stemming from subduction zone changes have, to our knowledge, never been quantified.

Conclusions

IPCC commentary regarding sea level centers strongly on the calculation and manipulation of changes in the theoretical global average. But realistic management of sea level and other environmental issues cannot be undertaken at a global level, but rather must acknowledge the many and varied ways in which geological anisotropy imposes its signature at local and regional scales. Isostatic change—which is influenced by such factors as water and ice loading, rates of seafloor spreading and subduction, and even phase changes in the upper mantle—imposes an inescapable uncertainty on predictions of future climate-related sea-level change. Such change will be regionally variable and mostly of small magnitude over centennial time scales.

References

Chappell, J.M.A. 1974. Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea level changes. *Geological Society of America Bulletin* **85**: 553–570.

Chappell, J., Chivas, A., Wallensky, E., Polach, H.A., and Aharon, P. 1983. Holocene paleo-environmental changes, central to north Great Barrier Reef inner zone. Bureau of Mineral Resources *Journal of Australian Geology and Geophysics* **8**: 223–236.

Clark, J.A. and Lingle, C.S. 1979. Predicted relative sea-level changes (18,000 Years B.P. to present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research* **11**: 279–298.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., and Oppenheimer, M. 2009. Probabilistic assessment of sea-level during the last interglacial stage. *Nature* **210**: 863–868.

Menard, H.W.. 1971. In: Turekian, K.K. (Ed.) *The Late Cenozoic Glacial Ages*. Yale University Press.

Pirazzoli, P.A., Grant, D.R., and Woodworth, P. 1989. Trends of relative sea-level change: past, present and future. *Quaternary International* **2**: 63–71. doi:10.1016/1040-6182(89)90022-0.

Tamisiea, M.E. and Mitrovica, J.X. 2011. The moving boundaries of sea-level change. *Oceanography* **24**: 24–39.

Van Vliet-Lanoe, B., Laurent, M., Bahain, J.L., Balescu, S., Falguères, C., Field, M., Hallégouët, B., and Keen, D.H. 2000. Middle Pleistocene raised beach anomalies in the English Channel: regional and global stratigraphic implications. *Journal of Geodynamics* **29**: 15–41.

6.2.1.8.2. GRACE

The conversion of satellite radar altimeter measurements into an accurate measure of the sea-surface level requires an accurate knowledge of both ocean mass and the shape of Earth, yet Earth's shape is constantly changing because of isostatic adjustments. Earth's shape is conventionally modeled as the geoid, which over the oceans is defined as the equipotential surface of Earth's gravity field that best fits, in a least squares sense, global mean sea level. One of the major difficulties of measuring sea-level changes from space is immediately apparent: The reference level is itself a function of the parameter being measured.

In 2002, twin orbiting satellites—the Gravity Recovery and Climate Experiment (GRACE)—were launched to provide better estimates of the ocean mass component of the sea-level budget. Although in principle the data provided by GRACE could lead to the accurate reconstruction of sea levels, the complex operational corrections that must be applied to spaceborne geophysical datasets mean “at best, the determination and attribution [in this way] of global-

mean sea level change lies at the very edge of knowledge and technology” (Wunsch *et al.*, 2007).

Part of the processing of GRACE data is its correction in terms of an assumed model for glacial isostatic adjustment (GIA). Disappointingly, data from the GRACE satellites have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and others.

NASA’s Jet Propulsion Laboratory (JPL) recently has acknowledged the importance of solving this problem by announcing a \$100 million mission to launch a Geodetic Reference Antenna in Space (GRASP) satellite to improve the measurement of the TRF (geoid) used to calculate satellite sea-level measurements (NASA JPL, 2012). JPL acknowledges the current lack of an accurate model of Earth’s reference frame has introduced spurious (and unknowable) errors into all satellite-borne sea-level, gravity, and polar ice cap volume measurements (Bar-Sever *et al.*, 2009).

A detailed analysis of processing and post-processing factors affecting GRACE estimates of ocean mass trends is provided by Quinn and Ponte (2010), who compare results from different GRACE data centers and explore a range of post-processing filtering and modeling parameters, including the effects of geocenter motion, postglacial isostatic rebound, and atmospheric pressure. Quinn and Ponte report the mean ocean mass trends they calculated “vary quite dramatically depending on which GRACE product is used, which adjustments are applied, and how the data are processed. For example, the isostatic rebound adjustment ranges from 1 to 2 mm/year, the geocenter adjustment may have biases on the order of 0.2 mm/year, and the atmospheric mass correction may have errors of up to 0.1 mm/year,” with differences between GRACE data centers also being large, up to 1 mm/year.

Despite the inherent uncertainty of the results, GRACE satellite data have been used in several studies to estimate sea-level rise due to global warming. The particularly confounding factor in these studies is that continental edges and ocean basins respond to past and recent mass loss or additions by rising or sinking (Gehrels, 2010). Thus a falling sea level could reflect glacial isostatic rebound at the same time the actual worldwide trend was one of increasing ocean mass and consequent sea-level rise; and vice versa.

Leuliette and Miller (2009) assert “Global mean sea level change results from two major processes that alter the total volume of the ocean,” and thus its mass. These processes are changes in total heat content and salinity, which produce density or steric changes; and the exchange of water between the oceans and other reservoirs, such as glaciers, icecaps, and land-based liquid water reservoirs. Although satellite radar altimeters have been providing data since the early 1990s, it is only since 2002 (GRACE) that global gravity estimates of mass variation have been available, and not until 2007 were accurate measurements made of global steric change (Argo ocean-profiling floats). It is probably for these reasons that prior attempts to close the global sea-level budget (Lombard *et al.*, 2007; Willis *et al.*, 2008) were unsuccessful.

Leuliette and Miller attempted a new analysis of the sea-level-rise budget for the period January 2004 to December 2007 using corrected Jason-1 and ENVISAT altimetric measurements, improved upper ocean steric data from the Argo array, and ocean mass variations calculated from GRACE gravity observations. The improved datasets closed the global sea-level-rise budget and indicated the sum of global steric sea level and ocean mass components had a trend of 1.5 ± 1.0 mm/year over the period of analysis. This result agrees with the measurements made by the Jason-1 (2.4 ± 1.1 mm/year) and ENVISAT (2.7 ± 1.5 mm/year) satellites within the 95% confidence interval.

Noting the last of these three results is 80 percent greater than the first, the question remains as to which result lies closest to the truth. Since Woppelmann *et al.* (2009) recently obtained a result of 1.58 ± 0.03 mm/year by analyzing GPS observations from a global network of 227 stations for the period 1997–2006, and given that both Church and White (2006) and Holgate (2007) obtained a result of 1.7 mm/year, it appears likely Leuliette and Miller (2009) have provided the most accurate result yet of any of the satellite altimeter studies.

Ivins *et al.* (2013) recalculated the contribution of Antarctic melt to sea-level rise using a claimed improved GIA correction. The GRACE data between January 2003 and January 2012, uncorrected for GIA, yield an ice mass rate of $+2.9 \pm 29$ Gt/yr. The new GIA correction increases the solved-for ice mass imbalance of Antarctica to -57 ± 34 Gt/yr. The revised GIA correction is smaller than past GRACE estimates by about 50 to 90 Gt/yr, leading to a new upper bound to sea-level rise from Antarctic melt over the averaged years about 0.16 ± 0.09 mm/yr.

Baur *et al.* (2013) used GRACE data to assess continental mass variations on a global scale, including both land-ice and land-water contributions, for 19 continental areas that exhibited significant signals. This was accomplished for the nine-year period 2002–2011 using the GIA model of Paulson *et al.* (2007) to remove the effects of isostatic adjustment. In contrast to previous authors, Baur *et al.* stress “present-day continental mass variation as observed by space gravimetry reveals secular mass decline and accumulation,” and “whereas the former contributes to sea-level rise, the latter results in sea-level fall.” Reliable overall estimates of sea-level change must consider mass accumulation, rather than solely mass loss. Baur *et al.* report the mean mass gain and mass loss in their 19 primary areas was -0.7 ± 0.4 mm/year of sea-level fall and $+1.8 \pm 0.6$ mm/year of sea-level rise, for a net effect of $+1.1 \pm 0.6$ mm/year. To obtain a figure for total sea-level change, a steric component of $+0.5 \pm 0.5$ mm/year (after Leuliette and Willis; 2011) was added, yielding a final uncorrected result of $+1.6 \pm 0.8$ mm/year or a geocenter-corrected result of $+1.7 \pm 0.8$ mm/year. These results are telling because the inferred rates of rise correspond almost exactly with the best- available independent measurements made with tide gauges (e.g., Church and White, 2006; Holgate, 2007).

Conclusions

Tide gauge reconstructions (Church and White, 2006) have found the rate of sea-level rise over the past century has been only 1.7 ± 0.5 mm/year. It seems strange to question this result using a GRACE-derived assessment with its many and potentially large errors and biases. Among other concerns, “non-ocean signals, such as in the Indian Ocean due to the 2004 Sumatran-Andean earthquake, and near Greenland and West Antarctica due to land signal leakage, can also corrupt the ocean trend estimates” (Quinn and Ponte, 2010).

Despite these problems, the latest GRACE estimates of Baur *et al.* (2012) correspond closely with their counterpart tide gauge estimates. Nonetheless, the GRACE satellites must develop a much longer history of satisfactory data acquisition before they can be considered a reliable means of providing accurate assessments of ocean mass and sea-level change. As Ramillien *et al.* (2006) have noted, “the GRACE data time series is still very short,” so any results obtained from it “must be considered as preliminary since we cannot exclude that apparent trends [derived from it] only reflect inter-annual fluctuations.”

References

- Bar-Sever, Y., Haines, B., Bertiger, W., Desai, S., and Wu, S. 2009. Geodetic reference antenna in space (GRASP)—a mission to enhance space-based geodesy. Jet Propulsion Laboratory, California Institute of Technology. http://ilrs.gsfc.nasa.gov/docs/GRASP_COSPAR_paper.pdf.
- Baur, O., Kuhn, M., and Featherstone, W.E. 2013. Continental mass change from GRACE over 2002–2011 and its impact on sea level. *Journal of Geodesy* **87**: 117–125.
- Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise, *Geophysical Research Letters* **33**: L01602, doi:10.1029/2005GL024826.
- Gehrels, R. 2010. Sea-level changes since the last glacial maximum: an appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science* **25**(1): 26–38. doi:10.1002/jqs.1273.
- Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* **34**: L01602, doi: 10.1029/2006GL028492, 2007.
- Ivins, E.R., James, T.S., Wahr, J., Schrama, E.J.O., Landerer, F.W., and Simon, K.M. 2013. Antarctic contribution to sea-level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*: n/a/n/a. doi:10.1002/jgrb.50208.
- Leuliette, E.W. and Miller, L. 2009. Closing the sea level rise budget with altimetry, Argo, and GRACE. *Geophysical Research Letters* **36**(4): doi: 10.1029/2008GL036010.
- Lombard, A., Garcia, D., Ramillien, G., Cazenave, A., Biancale, R., Lemoine, J., Flechtner, F., Schmidt, R., and Ishii, M. 2007. Estimation of steric sea level variations from combined GRACE and Jason-1 data. *Earth and Planetary Science Letters* **254**: 194–202.
- NASA JPL, 2012. Satellite mission GRASP. http://ilrs.gsfc.nasa.gov/missions/satellite_missions/future_missions/index.html.
- Paulson, A., Zhong, S., and Wahr, J. 2007. Inference of mantle viscosity from GRACE and relative sea level data. *Geophysical Journal International* **171**: 497–508.
- Quinn, K.J. and Ponte, R.M. 2010. Uncertainty in ocean mass trends from GRACE. *Geophysical Journal International* **181**: 762–768.
- Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R. 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change* **53**: 198–208.
- Willis, J.K., Chambers, D.P., and Nerem, R.S. 2008.

Assessing the globally averaged sea-level budget on seasonal to interannual timescales, *Journal of Geophysical Research* **113**: C06015, doi:10.1029/2007JC004517.

Woppelmann, G., Letetrel, C., Santamaria, A., Bouin, M.N., Collilieux, X., Altamimi, Z., Williams, S.D.P., and Martin Miguez, B. 2009. Rates of sea-level change over the past century in a geocentric reference frame. *Geophysical Research Letters* **36**: L12607, doi:10.1029/2009GL038720.

Wunsch, C., Ponte, R.M., and Heimbach, P. 2007. Decadal trends in sea-level patterns: 1993–2004. *Journal of Climate* **20**(24): 5889–5911. doi: 10.1175/2007JCLI1840.1.

6.2.1.9. Computer modeling

Graphs projecting future sea level can be constructed in three ways: empirical, semi-empirical, and deterministic modeling. Papers using these techniques are referred to in many other places in this chapter; here we discuss the modeling techniques themselves.

6.2.1.9.1 Empirical models

An empirical model is constructed by plotting a series of mean sea-level measurements against time and then summarizing any trend present by fitting a statistical model, usually the best-fit straight line, to the ensemble of points (e.g., Figure 6.2.1.3.3 above). Extrapolation of the assumed relationship can be used to project future sea-level positions. These techniques fit a statistical relationship to existing data in order to provide some basis for extrapolation beyond the period of the dataset; importantly, this method provides rigorous estimates of the uncertainty of the projections made and therefore also provides measures of their goodness of fit.

In general, extrapolation of an empirical model cannot extend very far beyond the limits of the original data (say 10 percent) before the confidence limits diverge widely. Therefore, empirical models cannot usefully predict sea level very far into the future. Nonetheless, a good-quality 100-year-long tide gauge record should provide about a 20-year forward prediction within reasonable confidence limits. This should be sufficient to manage coastal development with a short design life and also to provide a good basis on which to develop adaptive and mitigation strategies.

6.2.1.9.2 Deterministic models

At the other extreme from empirical modeling in terms of computational complexity are deterministic computer programs. Based on the fundamental laws of physics, deterministic models can be used to make calculations of the likely position of future sea level based on theoretical grounds. The procedure involves initially developing scenarios of future economic activity and hence potential emissions of greenhouse gases. These scenarios are used to estimate the changes in radiative forcing and hence changes in global temperature. These data are then used in turn to estimate the response of the oceans and cryosphere in terms of ice melt, thermal expansion, and sea-level change.

Such modeling is based on the assumptions that all relevant factors are known and taken into account, that adequate theoretical understanding exists and can be expressed mathematically, and that the scenarios considered capture the actual trajectory of future events. These assumptions are not necessarily true.

The general circulation model (GCM) calculations of IPCC research groups are of the deterministic type (see Figure 6.2.1.9.1), and their outcomes are referred to as *projections* because, unlike empirical predictions, they do not have statistically meaningful confidence limits.

The projected changing global sea level generated by ocean warming and ice melting comprises the kernel of the IPCC's computer models

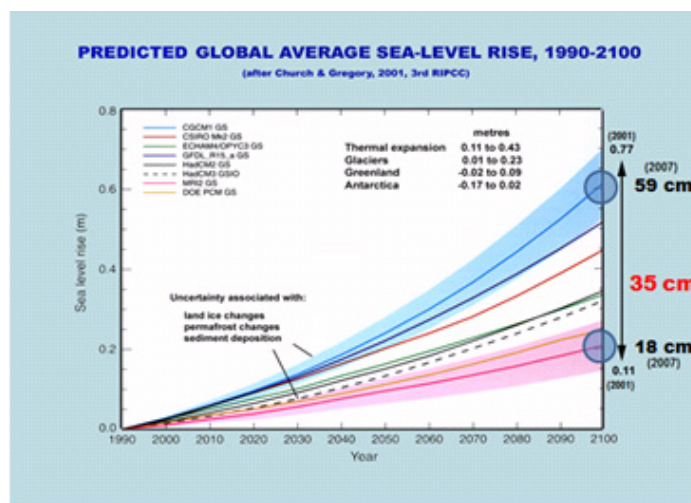


Figure 6.2.1.9.1. IPCC projections of sea-level rise between 1990 and 2100. Adapted from Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change*.

of the climate system. Ocean expansion can be directly related to warming of the surface mixed layer, but the melting of land ice is a more complex calculation that requires precise specification of surface temperatures. Ice does not necessarily melt if the surface temperature rises above 0°C; a small error can therefore make the difference between no melting and no sea-level change or actual melting and sea-level rise.

One difficulty with the deterministic approach is that it has proved difficult to identify the relative contributions to historical sea-level rise associated with the parameters modeled, so sea-level models have not predicted past sea levels well. It therefore remains unclear precisely how glacier and ice sheet behavior contribute to sea-level changes, although progress has been made since the first formal working group started their investigations in 1983 (Pfeffer, 2011). Thermosteric and halosteric sea-level changes also are not well constrained (Johnson and Wijffels, 2011). Since the Argo ocean-temperature profiling float array became fully operational in November 2007, some progress has been made on balancing the sea-level budget for the past decade (Leuliette and Willis, 2011), but it is not yet possible to extend the relationships back into the past with any degree of confidence (Wunsch *et al.*, 2007).

The range of possible future sea-level changes projected by the IPCC and its predecessors has decreased progressively since the earliest reports produced for the UNEP (Hoffman *et al.*, 1983). Due to the wide range of early projections and uncertainty about their validity, a future sea-level rise of 1 meter was commonly assumed for coastal impact assessments (SCOR Working Group 89, 1991), and that projection was included in the IPCC's *Second Assessment Report* in 1995. Considering the projections then currently used for coastal management, in its 2001 *Third Assessment Report* the IPCC provided a range of computer-generated projections for sea-level rise by 2100 of between 11 cm and 77 cm (Figure 6.2.1.9.1). They also estimated the current rate of sea-level rise of +1.8 mm/y was made up of contributions of 0.4 mm/y from thermal ocean expansion, 0.7 mm/y from ice melt, and 0.7 mm/y from dynamic oceanographic causes.

In the 2007 *Fourth Assessment Report* and using similar modeling, the IPCC adjusted the projected rise of sea level in 2100 to a range of 18–59 cm. The bottom end of this range corresponds with the 18 cm rise in sea level that results from extrapolating out to 2100 the long-term tide gauge rate of rise of 1.8 mm/y.

Church *et al.* (2011) compared the projections tuned by tide gauge data against the satellite altimetry trends, and Church and White (2011) reconstructed tide gauge data, concluding sea level is rising at the upper end of the IPCC projections. In contrast, the long-term tide-gauge-based sea-level rise reported by Church and White (1.7±0.2 mm/y), which they note is consistent with many other studies, falls right at the bottom of the IPCC projections (1.8 mm/y).

References

- Church, J.A. and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st century: *Surveys in Geophysics* **32**: 585–602.
- Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/2011GL048794.
- Hoffman, J.S., Keyes, D., and Titus, J.G. 1983. *Projecting future sea-level rise: methodology, estimates to the year 2100, and research needs*. United Nations Environmental Programme.
- Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change*.
- Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis. Summary for Policy Makers. 4th Assessment Report of the IPCC*.
- Johnson, G.C. and Wijffels, S.E. 2011. Ocean density change contributions to sea-level rise. *Oceanography* **24**(2): 112–121
- Pfeffer, W.T. 2011. Land ice and sea-level rise. *Oceanography* **24**(2): 95–111
- SCOR Working Group 89, 1991. The response of beaches to sea level changes: a review of predictive models. *Journal of Coastal Research* **7**: 895–921.
- Wunsch, C., Ponte, R.M., and Heimbach, P. 2007. Decadal trends in sea-level patterns: 1993–2004. *Journal of Climate* **20**(24): 5889–5911. 0.1175/2007JCLI1840.1.

6.2.1.9.3 Semi-empirical models

Between empirical and deterministic models lie other modeling techniques of moderate complexity that are collectively termed semi-empirical models. These models derive a relationship between sea level and

temperature and then combine that relationship with a projected temperature scenario to estimate future sea-level rise. To their proponents, semi-empirical models are attractive because they are claimed to be superior to empirical models in making projections far into the future. Some of the most frequently cited are those by Rahmstorf (2007a), Vermeer and Rahmstorf (2009), Grinstead *et al.* (2010), and Rahmstorf *et al.* (2012).

The published results from semi-empirical models produce the highest and most alarming estimates of rates of future sea-level change so far published (between 0.8 and 1.8 m by 2100), and they conflict with projections based upon empirical or deterministic modeling. Accordingly, they are controversial and have attracted substantial criticism in the peer-reviewed scientific literature (Holgate *et al.*; Schmith *et al.*, 2007; Rahmstorf, 2007b).

The first of the semi-empirical studies (Rahmstorf, 2007a) proposed sea-level rise is a lagged response to temperature rise due to the greenhouse effect heating the ocean; the contribution from melting ice is also said to be a delayed response. These assumptions are directly contradicted by our knowledge of the last post-glacial sea-level rise (PALSEA, 2010; Section 6.2.1.1). In addition, the iterative smoothing process used by Rahmstorf during analysis has the effect of truncating the declining rate of sea-level rise observed in recent decades and inflating the correlation between sea level and temperature. The modeling also depends on the accuracy of IPCC emission scenarios known to be inaccurate (Castles and Henderson, 2003).

Some of these criticisms were taken into account in a modified version of the model, which includes an additional term and uses less smoothing, published by Vermeer and Rahmstorf (2009) (see Figure 6.2.1.9.2). However, the new term in the model reduces the effect of the slower rate of sea-level rise observed this century and maximizes the faster rate of the 1990s. These observed changes correspond to well-recognized decadal variability that is neither taken into account nor replicated in the 2009 Vermeer and Rahmstorf study.

The most recent iteration of Rahmstorf's semi-empirical model was published by Rahmstorf *et al.* (2012). This version of the model utilized several sea-level reconstructions, although only three are reported in the paper: the initial Church and White (2006) reconstruction; the revised global sea-level reconstruction of Church and White (2011); and the Jevrejeva *et al.* (2009) reconstruction. The 2011 reconstruction led to lower future sea-level rise than the older datasets, leading Rahmstorf *et al.* (2012) to

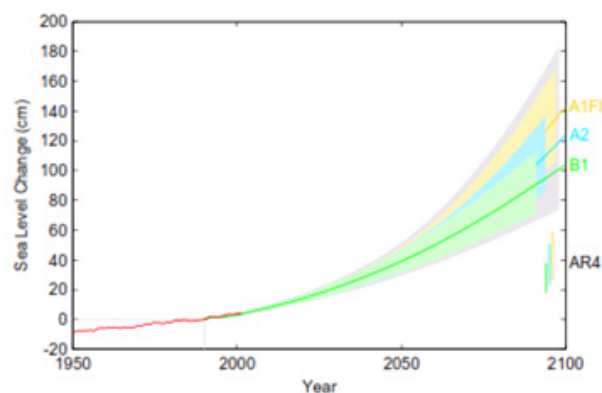


Figure 6.2.1.9.2. Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three emission scenarios (labeled on right). Adapted from Vermeer, M. and Rahmstorf, S. 2009. Global sea-level linked to global temperature, *Proceedings of the National Academy of Sciences* **106**: 21527–21532, Figure 6.

argue the 2009 projection (based on outdated data) is the most accurate.

The semi-empirical models suffer from a fatal flaw: They include no probability analysis. Yes, these studies project the possible magnitude of a future rise. But because hazard is defined in terms of both magnitude and frequency, by not expressing the probability they give only one half of the story. The important other half is that although a higher rate of rise than that observed historically is possible, it is also extremely unlikely.

Conclusions

The controversy surrounding the accuracy and policy usefulness of published semi-empirical models of sea-level change remains unresolved. Semi-empirical models have several known flaws, and given that both empirical and GCM modeling yield more modest projections of future sea level, semi-empirical model projections should be viewed with caution until their flaws are addressed (e.g., Church *et al.*, 2011).

References

- Castles, I. and Henderson, D. 2003. The IPCC emission scenarios: an economic-statistical critique. *Energy and Environment* **14**: 159–185.
- Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise, *Geophysical Research Letters* **33**: L01602, 10.1029/2005GL024826.
- Church, J.A. and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* **32**: 585–602.

Observations: The Hydrosphere and Oceans

Grinsted, A., Moore, J.C., and Jevrejeva, S. 2010. Reconstructing sea-level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* **34**(4): 461–472.

Jevrejeva, S., Grinsted, A., and Moore, J.C. 2009. Anthropogenic forcing dominates sea level rise since 1850. *Geophysical Research Letters* **36**: 10.1029/2009GL040216

Rahmstorf, S. 2007a. A semi-empirical approach to projecting future sea-level rise. *Science* **315**: 368–370.

Rahmstorf, S. 2007b. Response to comments on “A semi-empirical approach to projecting future sea-level rise.” *Science* **317**: 1866–1866.

Rahmstorf, S., Perrette, M., and Vermeer, M. 2012. Testing the robustness of semi-empirical sea-level projections: *Climate Dynamics* **39**: 861–875.

Vermeer, M. and Rahmstorf, S. 2009. Global sea-level linked to global temperature, *Proceedings of the National Academy of Sciences* **106**: 21527–21532.

6.2.1.10. Mechanisms of sea-level change

Key issues in understanding eustatic (global) sea-level change include the degree to which glacial meltwater is causing an increase in ocean mass, the degree to which global warming may be causing thermosteric ocean expansion and hence sea-level rise, and the relative magnitude of direct human interferences with the fresh water budget such as dam building and ground water mining.

Research on most of these topics has been touched upon in many of the preceding sections of this chapter. We add below summaries of a small number of other papers conveniently handled under the three subheadings of 6.2.1.10.

6.2.1.10.1. Ice melt

Earlier Research

Papers addressing the issue of land-based ice melt as a cause of global sea-level rise include the following:

- Bindshadler (1998) analyzed the historical retreat of the West Antarctic Ice Sheet in terms of its grounding line (the boundary between the floating ice shelf and the “grounded” ice resting on bedrock) and ice front. He found the retreat of the ice sheet’s grounding line has been faster than that of its ice front since the time of the last glacial maximum, which resulted in an expanding Ross Ice Shelf. Although the ice front now appears to be nearly stable, there are

“indications that its grounding line was retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years.” Such a retreat would result in a sustained sea-level rise of 8–13 cm per century. Bindshadler acknowledges even the smallest of these rates of rise would require a large negative mass balance for all of West Antarctica, a finding not supported by the data.

- Reeh (1999) summarized earlier work on the mass balance of the Greenland and Antarctic ice sheets. He concluded their future contribution to global sea level depends as much upon their past climatic and dynamic history as it does upon future climate. With respect to potential climate change, Reeh estimated a 1°C warming would create little net change in mean global sea level; Greenland’s contribution would be a sea-level rise of only 0.30 to 0.77 mm/yr, while Antarctica’s contribution, given that it is accreting mass, would be a sea-level fall of about 0.20 to 0.70 millimeters per year.

- Vaughn *et al.* (1999) used more than 1,800 measurements of the surface mass balance of Antarctica to produce an assessment of yearly ice accumulation over the continent. They found the “total net surface mass balance for the conterminous grounded ice sheet is 1,811 Gt yr⁻¹ (149 kg m⁻² yr⁻¹) and for the entire ice sheet including ice shelves and embedded ice rises, 2,288 Gt yr⁻¹ (166 kg m⁻² yr⁻¹).” These values are about 18 percent and 7 percent higher than current estimates derived about 15 years earlier. Some of the discrepancy may be explained by changes in net icefall over more recent years. The uncertainty leads Vaughn *et al.* to note, “we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea-level change.”

- Cuffey and Marshall (2000) reevaluated previous model estimates of the Greenland ice sheet’s contribution to sea-level rise during the last interglacial using a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. Their results suggest the Greenland ice sheet was much smaller during the last interglacial than previously thought, with melting of the ice sheet then contributing between 4 and 5.5 meters to sea-level rise. Hvidberg (2000) noted this finding suggests “high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change.”

- Wild and Ohmura (2000) studied the mass balance of Antarctica using two general circulation

models developed at the Max Planck Institute for Meteorology in Hamburg, Germany: the older ECHAM3 and a new and improved ECHAM4. Under a doubled atmospheric CO₂ scenario, the two models were in close agreement in their mass balance projections, with both predicting increases in ice sheet growth and therefore decreases in sea level.

- Van der Veen (2002) stressed the need to use probability density functions rather than single model outputs for policy-related sea-level research. He comments, “the validity of the parameterizations used by [various] glaciological modeling studies to estimate changes in surface accumulation and ablation under changing climate conditions has not been convincingly demonstrated.” Uncertainties in model parameters are so great they yield a 95% confidence range of projected meltwater contributions from Greenland and Antarctica that encompass global sea-level lowering as well as rise by 2100 A.D., for all of IPCC’s low, middle, and high warming scenarios. Van der Veen concluded confidence in current ice sheet mass balance models “is quite low,” today’s best models “currently reside on the lower rungs of the ladder of excellence,” and “considerable improvements are needed before accurate assessments of future sea-level change can be made.”

- Wadhams and Munk (2004) attempted “an independent estimate of eustatic sea-level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level).” Their analysis produced “a eustatic rise of only 0.6 mm/year,” and when a steric contribution of 0.5 mm/year is added to the eustatic component, “a total of 1.1 mm/year, somewhat less than IPCC estimates,” was the final result. Interestingly, the continental runoff “allowed” after subtracting the effect of sea-ice melt “is considerably lower than current estimates of sub-polar glacial retreat”; consonant with the mass balance models discussed above, this suggests a negative contribution to sea-level from polar ice sheets (Antarctica plus Greenland) or other non-glacial processes. Wadhams and Munk note, “we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive or negative contribution.”

- Oppenheimer and Alley (2005) discuss the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other, for both the

West Antarctic and Greenland Ice Sheets. They conclude our knowledge is simply too incomplete to know whether these ice sheets have made a significant contribution to sea-level rise over the past few decades.

- Velicogna and Wahr (2006) used early measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the period 2002–2005. The two researchers conclude “the ice sheet mass decreased significantly, at a rate of $152 \pm 80 \text{ km}^3/\text{yr}$ of ice, equivalent to $0.4 \pm 0.2 \text{ mm/yr}$ of global sea-level rise.” All of this mass loss came from the West Antarctic Ice Sheet; the East Antarctic Ice Sheet mass balance was $0 \pm 56 \text{ km}^3/\text{year}$.

The Velicogna and Wahr conclusion should be viewed as provisional because of the many estimates and adjustments necessary during data reduction (see Section 6.2.1.8 for additional comments on the difficulty of using GRACE data). The adjustment for post-glacial rebound alone exceeded the signal being sought by nearly a factor of five. Moreover, the study covers less than a three-year period, and the result compares poorly with the findings of Zwally *et al.* (2005), who determined Antarctica’s contribution to mean global sea level over a recent nine-year period was only 0.08 mm/yr.

- Ramillien *et al.* (2006) also used GRACE data to derive mass balance estimates for the East and West Antarctic ice sheets for the years 2002–2005. They calculated a loss of $107 \pm 23 \text{ km}^3/\text{year}$ for West Antarctica and a gain of $67 \pm 28 \text{ km}^3/\text{year}$ for East Antarctica, totaling a net ice loss for the entire continent of $40 \text{ km}^3/\text{year}$, a mean sea-level rise of 0.11 mm/year. This result is almost four times less than that calculated by Velicogna and Wahr. Ramillien *et al.* caution in their closing paragraph, “the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations.”

- Wingham *et al.* (2006) analyzed European remote sensing satellite altimeter data to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. They found “72% of the Antarctic ice sheet is gaining $27 \pm 29 \text{ Gt}$ per year, a sink of ocean mass sufficient to lower global sea levels by 0.08 mm per year.” Wingham *et al.* contend this net extraction of water from the global ocean was driven by mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica.

Observations: The Hydrosphere and Oceans

- Remy and Frezzotti (2006) reviewed the results produced by estimating mass balance in three ways: measuring the difference between mass input and output; monitoring the changing geometry of Antarctica; and modeling both the dynamic and climatic evolution of the continent. They report “the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale [centuries].” They also note, “later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level.”

- Shepherd and Wingham (2007) reviewed 14 satellite-based estimates of sea-level contributions arising from wastage of the Antarctic and Greenland Ice Sheets since 1998. The earlier studies included standard mass budget analyses, altimetry measurements of ice-sheet volume changes, and measurements of the ice sheets’ changing gravitational attraction. The results ranged from a sea-level-rise-equivalent of 1.0 mm/year to a sea-level-fall-equivalent of 0.15 mm/year. Shepard and Wingham concluded the current best estimate of the contribution of polar ice wastage from Greenland and Antarctica to global sea-level change was a rise of 0.35 mm/yr, i.e., a rate of 35 mm/century.

An important factor in many of these ice budget papers is the degree to which glacial wastage rates vary from year to year. For example, two of Greenland’s largest outlet glaciers doubled their rates of mass loss in less than a year in 2004—causing the IPCC to claim the Greenland Ice Sheet was responding much more rapidly to global warming than expected—but by 2006 the mass loss had decreased to near the previous rates. Thus Shepherd and Wingham warn “special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends.”

- Krinner *et al.* (2007) applied the LMDZ4 atmospheric general circulation model of Hourdin *et al.* (2006) to simulate Antarctic climate for the periods 1981–2000 (to test the model’s ability to adequately simulate recent conditions) and 2081–2100 (to assess the future mass balance of the Antarctic Ice Sheet and its impact on global sea level). They conclude the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year, which corresponds to a sea-level decrease of

1.2 mm per year by the end of the twenty-first century. This would lead to a cumulated sea-level decrease of about 6 cm. They note the simulated temperature increase “leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air,” where the extra moisture falls as precipitation and causes the continent’s ice sheet to grow.

- In a study of Alaskan and nearby Canadian glaciers, Berthier *et al.* (2010) pointed out earlier estimates of mass loss from Alaskan and nearby glaciers (Arendt *et al.*, 2002; Meier and Dyurgerov, 2002; Dyurgerov and Meier, 2005) relied on extrapolating site-specific measurements to the entire region. For example, Arendt *et al.* (2002) used laser altimetry to measure elevation changes on 67 glaciers, but those glaciers represented only 20 percent of the area of the ice field.

To overcome this and other deficiencies, Berthier *et al.* attempted to calculate ice elevation changes for nearly three-quarters of the ice-covered areas in Alaska by measuring elevation changes derived from sequential digital elevation models for the period 1962–2006. They found, “between 1962 and 2006, Alaskan glaciers lost $41.9 \pm 8.6 \text{ km}^3$ of their volume over the measured period, thereby contributing $0.12 \pm 0.02 \text{ mm/yr}$ to sea-level rise.” This estimate is 34 percent less than those of Arendt *et al.* (2002) and Meier and Dyurgerov (2002), an indication of the inherent errors in this type of research. Berthier *et al.* comment, “estimates of mass loss from glaciers and ice caps in other mountain regions could be subject to similar revisions.”

- Nick *et al.* (2013) developed a glacier flow model incorporating the dynamic behavior of marine glacial termini affected by ocean conditions. This model was applied to four marine-terminating glaciers that account for 22 percent of the flow from the Greenland Icecap. Assuming 2.8° C of warming by 2100, they simulated the atmospheric and oceanic effects on ice discharge and projected a sea-level contribution of 19–30 mm by AD 2200 ($0.01\text{--}0.06 \text{ mm/y}$ per glacier after an initial rapid loss associated with over-deepening in the glacier troughs). These estimates are considerably lower than those derived by Pfeffer *et al.* (2008) of 36–118 mm for the 22 percent of glacier flow (or 165–538 mm for all of Greenland) by AD 2100.

Conclusions

Considerable uncertainty attends our knowledge of the water balance of the world’s oceans and the melting of on-land ice. These uncertainties must be

resolved before we can confidently project effects such as sea-level change.

It appears there has been little recent change in global sea level due to wastage of the West Antarctic Ice Sheet, and such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall. In such circumstances the sum of the response of the whole Antarctic Ice Sheet might well compensate for any long-term wastage of the Greenland Ice Sheet, should that happen.

Regarding the Northern Hemisphere, the Arctic regions have been cooling for the past half-century, and at a very significant rate, making it unlikely Greenland's frozen water will be released to the world's oceans anytime soon. This temperature trend is just the opposite—and strikingly so—of that claimed for the Northern Hemisphere and the world by the IPCC. Accompanying the cooling, the annual number of snowfall days over parts of Greenland has also increased strongly, so an enhanced accumulation of snow there may be compensating for the extra runoff coming from mountain glaciers that have been receding.

The balance of the evidence from both hemispheres indicates little net sea-level change is currently occurring as a result of accentuated ice melt. It remains entirely possible the global cryosphere is actually growing in mass.

References

- Arendt, A.A., Echelmeyer, K.A., Harrison, W.D., Lingle, C.S., and Valentine, V.B. 2002. Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science* **297**: 382–386.
- Berthier, E., Schiefer, E., Clarke, G.K.C., Menounos, B., and Remy, F. 2010. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geoscience* **3**: 92–95.
- Bindschadler, R. 1998. Future of the West Antarctic Ice Sheet. *Science* **282**: 428–429.
- Cuffey, K.M. and Marshall, S.J. 2000. Substantial contribution to sea-level rise during the last interglacial from the Greenland ice sheet. *Nature* **404**: 591–594.
- Dyurgerov, M.B. and Meier, M.F. 2005. *Glaciers and the Changing Earth System: A 2004 Snapshot*. Instaar.
- Hourdin, F., Musat, I., Bony, S., Braconnot, P., Codron, F., Dufresne, J.L., Fairhead, L., Filiberti, M.A., Friedlingstein, P., Grandpeix, J.Y., Krinner, G., Le Van, P., Li, Z.X., and Lott, F. 2006. The LMDZ4 general circulation model: climate performance and sensitivity to parameterized physics with emphasis on tropical convection. *Climate Dynamics* **27**: 787–813.
- Hvidberg, C.S. 2000. When Greenland ice melts. *Nature* **404**: 551–552.
- Krinner, G., Magand, O., Simmonds, I., Genthon, C., and Dufresne, J.-L. 2007. Simulated Antarctic precipitation and surface mass balance at the end of the twentieth and twenty-first centuries. *Climate Dynamics* **28**: 215–230.
- Meier, M.F. and Dyurgerov, M.G.B. 2002. Sea level changes: How Alaska affects the world. *Science* **297**: 350–351.
- Nick, F.M., Vieli, A., Andersen, M.A., Joughin, I., Payne, A., Edwards, T.L., Pattyn, F., and van de Wal, R.S.W. 2013. Future sea-level rise from Greenland's main outlet glaciers in a warming climate. *Nature* **497**: 235–238.
- Oppenheimer, M. and Alley, R.B. 2005. Ice sheets, global warming, and article 2 of the UNFCCC. *Climatic Change* **68**: 257–267.
- Pfeffer, W.T., Harper, J.T., and O'Neel, S. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* **321** (5894) (September 5): 1340–1343. doi:10.1126/science.1159099.
- Ramillien, G., Lombard, A., Cazenave, A., Ivins, E.R., Llubes, M., Remy, F., and Biancale, R. 2006. Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change* **53**: 198–208.
- Reeh, N. 1999. Mass balance of the Greenland ice sheet: can modern observation methods reduce the uncertainty? *Geografiska Annaler* **81A**: 735–742.
- Remy, F. and Frezzotti, M. 2006. Antarctica ice sheet mass balance. *Comptes Rendus Geoscience* **338**: 1084–1097.
- Shepherd, A. and Wingham, D. 2007. Recent sea-level contributions of the Antarctic and Greenland ice sheets. *Science* **315**: 1529–1532.
- van der Veen, C.J. 2002. Polar ice sheets and global sea level: how well can we predict the future? *Global and Planetary Change* **32**: 165–194.
- Vaughn, D.G., Bamber, J.L., Giovinetto, M., Russell, J., and Cooper, A.P.R. 1999. Reassessment of net surface mass balance in Antarctica. *Journal of Climate* **12**: 933–946.
- Velicogna, I. and Wahr, J. 2006. Measurements of time-variable gravity show mass loss in Antarctica. *Scienceexpress*: 10.1126/science.1123785.
- Wadhams, P. and Munk, W. 2004. Ocean freshening, sea level rising, sea ice melting. *Geophysical Research Letters* **31**: 10.1029/2004GL020039.

Wild, M. and Ohmura, A. 2000. Change in mass balance of polar ice sheets and sea level from high-resolution GCM simulations of greenhouse warming. *Annals of Glaciology* **30**: 197–203.

Wingham, D.J., Shepherd, A., Muir, A., and Marshall, G.J. 2006. Mass balance of the Antarctic ice sheet. *Philosophical Transactions of the Royal Society A* **364**: 1627–1635.

Zwally, H.J., Giovinetto, M.B., Li, J., Cornejo, H.G., Beckley, M.A., Brenner, A.C., Saba, J.L., and Yi, D. 2005. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *Journal of Glaciology* **51**: 509–527

6.2.1.10.2. Thermosteric

Lombard *et al.* (2005) used the global ocean temperature data of Levitus *et al.* (2000) and Ishii *et al.* (2003) to investigate the thermosteric, or temperature-induced, sea-level change of the past 50 years. A net rise in sea level occurred over the full half-century period, but superimposed on that are marked decadal oscillations that represent ocean-atmosphere climatic perturbations such as the El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation. Lombard *et al.* recognized these as thermosteric trends over 10-year windows that showed large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (-1 to -1.5 mm/year for the decade centered on 1980).

The record shows only an overall trend because it began at the bottom of a trough and ended at the top of a peak. In between these two points, there were both higher and lower values, so one cannot be sure what would be implied if earlier data were available or what will be implied as more data are acquired. Lombard *et al.* noted similar sea-level trends that occur in TOPEX/Poseidon altimetry over 1993–2003 are “mainly caused by thermal expansion” and thus probably not a permanent feature. They conclude, “we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone.”

If even the 50 years of global ocean temperature data we possess are insufficient to identify accurately the degree of global warming and related sea-level rise that has occurred over the past half-century, it will be many decades before satellite altimetry can identify a real climatic trend.

References

Ishii, M., Kimoto, M., and M. Kachi, M. 2003. Historical ocean subsurface temperature analysis with error estimates. *Monthly Weather Review* **131**: 51–73.

Levitus, S., Antonov, J.L., Boyer, T.P., and Stephens, C. 2000. Warming of the world ocean. *Science* **287**: 2225–2229, doi:10.1126/science.287.

Lombard, A., Cazenave, A., Le Traon, P.-Y., and Ishii, M. 2005. Contribution of thermal expansion to present-day sea-level change revisited. *Global and Planetary Change* **47**: 1–16.

6.2.1.10.3. Dam storage and groundwater depletion

Two human on-land development practices can have a material effect on sea level: the building of dams and reservoirs, which withhold water that would otherwise have flowed to the ocean; and the extraction of groundwater, which, after use, contributes water to the ocean that otherwise would have remained stored on the continent. The net freshwater run-off is thereby altered, with the first practice acting to lower sea level and the second practice helping to raise it.

Though they act in opposite directions and are small in the natural scheme of things, these effects are not entirely negligible (e.g., Sahagian *et al.*, 1994; Gornitz *et al.*, 1997; Konikow and Kendy, 2005; Huntington, 2008; Lettenmaier and Milly, 2009; Milly *et al.*, 2010). Konikow (2011) recently summarized the situation with respect to groundwater removal by compiling the first comprehensive aquifer-based estimate of changes in groundwater storage using direct volumetric accounting. Konikow then compared the groundwater depletion results he obtained with sea-level rise observations.

Konikow established groundwater depletion over the period 1900–2008 was about 4,500 km³, equivalent to a global sea-level rise of 12.6 mm, or just over 6 percent of the total observed rise. Perhaps not surprisingly, the rate of groundwater depletion has increased markedly since about 1950, with maximum rates occurring during the most recent period (2000–2008), when extraction averaged ~145 km³/year. The average rate of sea-level rise over the twentieth century was 1.8 ± 0.5 mm/year (Church *et al.*, 2011); Konikow’s work suggests on average 0.12 mm/yr of this rise may have resulted from additional groundwater runoff.

References

- Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/2011GL048794.
- Gornitz, V., Rosenzweig, C., and Hillel, D. 1997. Effects of anthropogenic intervention in the land hydrologic cycle on global sea level rise. *Global and Planetary Change* **14**: 147–161.
- Huntington, T.G. 2008. Can we dismiss the effect of changes in land-based water storage on sea-level rise? *Hydrological Processes* **22**: 717–723.
- Konikow, L.F. 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters* **38**: 10.1029/2011GL048604.
- Konikow, L.F. and Kendy, E. 2005. Groundwater depletion: A global problem. *Hydrogeology Journal* **13**: 317–320.
- Lettenmaier, D. and Milly, P.C.D. 2009. Land waters and sea level. *Nature Geoscience* **2**: 452–454.
- Milly, P.C.D., Cazenave, A., Famiglietti, J.S., Gornitz, V., Laval, K., Lettenmaier, D.P., Sahagian, D.L., Wahr, J.M., and Wilson, C.R. 2010. Terrestrial water-shortage contributions to sea-level rise and variability. In: Church, J.A., Woodworth, P.L., Aarup, T., and Wilson, W.S. (Eds.) *Understanding Sea-Level Rise and Variability*. Wiley-Blackwell, Oxford, United Kingdom, pp. 226–255.
- Sahagian, D.L., Schwartz, F.W., and Jacobs, D.K. 1994. Direct anthropogenic contributions to sea level rise in the twentieth century. *Nature* **367**: 54–57.
- tectonic factors, isostatic effects, and multidecadal rhythmicity to produce different patterns of local relative sea-level change that vary from place to place and region to region (Figure 6.2.1.8.1.1). It is also established by many studies that over the past 150 years eustatic sea level has been rising at an average rate of about 1.8 mm/y, which represents the slow continuation of a melting of the ice sheets that began about 17 ka. The IPCC estimates 1.1 mm of this rise can be accounted for by the combined effects of continuing ice melt (~0.4 mm/y) and steric ocean expansion (~0.7 mm/y), and that the residuum, if correctly estimated, probably relates to dynamic oceanographic and meteorological factors.
- There is, therefore, no scientific basis for the oft-repeated suggestion that “global warming” will melt so much ice that sea levels will imminently rise by Al Gore’s imagined 20 feet. In four successive *Assessment Reports* between 1990 and 2007, the IPCC has reduced its estimate of the maximum sea-level rise by the year 2100 from 367 to 124 to 77 to 59 cm, a reduction of the speculated rise of more than 80 percent. Moreover, IPCC 2007 assumed most of the projected increase arises from a slow (centuries) thermosteric expansion of the oceans, which produces a sea-level rise of only 20–60 cm per 1°C increase in globally averaged warming (Church *et al.*, 2011). Furthermore, warming is currently not occurring at the projected rate. Should they continue to melt, glaciers and ice caps are expected to contribute another 12±4 cm by 2100 (Church *et al.*, 2011). Ice sheet contributions are less certain because of large variations in estimates of ice volume losses. However, an upper estimate based on extrapolating a short record is 56 cm by 2100 (Pfeffer, 2011).

6.2.1.11. Policy: What is the problem?

The fear that human carbon dioxide emissions may cause dangerous sea-level rise beyond natural rates and levels has focused policy attention on cutting emissions. The preceding parts of Section 6.2 have demonstrated there is very little evidence to support the CO₂-sea level rise hypothesis. No evidence (as opposed to computer model speculation) shows the human component of atmospheric carbon dioxide levels is materially influencing sea level to behave outside its usual natural envelope of change.

Based on geological studies, it appears global sea-level rise has been taking place at a slowing rate over the past 10,000 years (cf., Figure 6.2.1.1.2). At specific locations, this rising trend interacts with

Conclusions

The problem is not global sea-level change, which, using a naïve forecasting approach, is projected to rise by only about 18 cm by 2100. Instead the problem is uncertainty. That uncertainty applies to future global temperature change, future ice accretion or melting, and future global sea-level change—and it is profound.

References

- Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/2011GL048794.

Observations: The Hydrosphere and Oceans

Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change*.

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis. Summary for Policy Makers. 4th Assessment Report of the Intergovernmental Panel on Climate Change*.

Pfeffer, W.T. 2011. Land ice and sea-level rise. *Oceanography* 24(2): 95–111.

Management and planning for the real hazard

Sea levels change naturally, constantly, and all over the world at different rates and in opposing directions. In addition, the effect of sea-level change is almost exclusively a matter of coastal management, a fact that has not been widely recognized. Outside of very shallow coastal waters, whether the sea level is higher or lower is of no practical concern for shipping activities or other human ocean uses such as erecting offshore petroleum production platforms or laying deep-sea communications cables. Thus at the heart of the issue of sea-level policy lies the need for an understanding of coastal processes.

The position and stability of a shoreline depends upon a number of factors. One of these is local mean sea level. But several other important natural processes also operate within and upon the coastal environment, including geomorphology, sediment supply, and mean and extreme conditions of wind, weather, and near-shore oceanography. The shoreline also is affected by human development.

In most countries, coastal management is traditionally undertaken by a local or regional council of some type, operating within a legal framework provided by either a state or national government (French, 1997). The local agencies deal with such matters as beach erosion and harbor dredging, and they establish and enforce land-use and building regulations addressing what types of structures may be built where. In implementing coastal policy, lawmakers and their staff traditionally have been guided by experienced, legally accountable, professional coastal engineers and scientists. Until recently, therefore, cost-benefit analysis of coastal policy was generally alive and well at the local and regional level of governance and administration.

Which is, of course, not to say historic coastal management has been perfect. One particular defect has been inadequate control over dense coastal development that later proves to be inadequately sited to withstand the effects of rare and episodic super

storms. The “hurricane” Sandy storm in northeastern USA provides a case in point. The strong wave surges and winds that imposed such destruction on the northeast’s poorly located coastal communities were caused by the merging of two separate storm systems. Though this was a rare event, in a general sense it was entirely predictable, and the occurrence of Sandy should act as a wake-up call for the need for more cautious attitudes to coastal development.

Since 1988, traditional, locally oriented coastal management has increasingly come to be replaced by planning based on global environmental principles, as the IPCC commenced advising governments about global sea-level change. The advent of IPCC’s global warming advice usurped the traditional policy process through which governments drew their advice about sea-level change from statutory authorities concerned with harbor and tidal management and from formal governmental scientific agencies. Because the IPCC is tasked to ponder global warming, after its formation the focus of governments shifted from seeing sea-level change as a beaches, ports, harbors, and navigational issue to seeing it as an environmental issue related to hypothetical global warming caused by human carbon dioxide emissions.

As part of this change, attention shifted away from basing public policy on the use of measured tide gauge records of sea level (see Figure 6.2.1.2.1) to basing it on the theoretical projections of computer models (such as Figures 6.2.1.9.1 and 6.2.1.9.2). By the turn of the twentieth century, governments around the world, and their advisory scientists, were basing their sea-level planning almost exclusively on the advice of the IPCC; i.e., on unvalidated computer model predictions tied not to accurate local sea-level measurements but to a theoretical geoid that floats in mathematical space.

Because IPCC sea-level predictions were and are for a global average sea level, we thus arrived at our present unsustainable position, which is one of governments fashioning policy and new laws predicated upon a notional statistic and in almost complete disregard of the local real measurements available from tide gauge networks. Many countries or states have passed measures that require their coastal authorities to base planning on IPCC’s assumed 59 cm rise by 2100, or higher. For example, the Australian states of Victoria and New South Wales have set planning benchmark levels of 80 cm and 90 cm, respectively.

Abandoning traditional, empirical methods of dealing with coastal management issues and adopting (sometimes exaggerating) the IPCC’s uncertain,

model-based sea-level projections has introduced much additional and unrecognized uncertainty into policy planning. Uncertainty surrounds the global temperature projections that feed into sea-level modeling and affects the relationship between global temperature change and polar land ice melting rates. Moreover, we lack accurate knowledge of the glacial isostatic anomaly.

Conclusions

Based on this discussion and the other material presented in this chapter, three obvious policy guidelines present themselves for implementation.

Abandon “let’s stop global sea-level rise” policies

No justification exists for continuing to base sea-level policy and coastal management regulation on the outcomes of deterministic or semi-empirical sea-level modeling. Such modeling remains highly speculative. Even if the rate of eustatic sea-level change was known accurately, the practice of using a notional global rate of sea-level change to manage specific coastal locations worldwide is irrational, and it should be abandoned.

Recognize the local or regional nature of coastal hazard

Most coastal hazard is intrinsically local in nature. Other than periodic tsunamis and exceptional storms, it is the regular and repetitive local processes of wind, waves, tides, and sediment supply that fashion the location and shape of the shorelines of the world.

Yes, local relative sea level is an important determinant, but in some localities it is rising and in others falling. Accordingly, there is no “one size fits all” sea-level curve or policy that can be applied. Coastal hazard can be managed effectively only in the context of regional and local knowledge and using data gathered by site-specific tide gauges and other relevant instrumentation.

Use planning controls that are flexible and adaptive

The shoreline is a dynamic geomorphic feature that quite naturally moves with time in response to changing environmental conditions. Many planning regulations already recognize this; for example, by applying minimum building setback distances or heights from the tide mark. In addition, engineering solutions (groynes, breakwaters, sea-defense walls) often are used to stabilize a shoreline. If they are effective and environmentally acceptable, such solutions should be encouraged.

Nevertheless, occasional damage will continue to

be imposed from time to time by large storms or other unusual natural events, no matter how excellent the preexisting coastal engineering and planning controls may be. In these circumstances, the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur. It is the height of futility and a waste of scarce financial resources to attempt to “control” the size or frequency of large natural events by expecting that reductions in human carbon dioxide emissions will moderate climate “favorably,” including expectations of a reduced rate of global sea-level rise.

Reference

French, P.W. 1997. Coastal and estuarine management. Routledge Environmental management series.

6.2.2. Ocean Heat

Earth’s climate is not controlled solely by the atmosphere but also to a large degree by the heat stored in the ocean, which has a 3,300 times greater heat capacity than the atmosphere. With an average global circulation time of roughly 1,000 years, compared with one year for the atmosphere, changes in the release or uptake of ocean heat operate over the longer multidecadal, centennial, and millennial time scales associated with climate change, as opposed to weather variability.

The exchange of ocean heat via currents and wind-enhanced ocean-atmosphere interactions drives weather at all scales of both space and time. Particular, repetitive weather patterns occur over the ocean itself and exercise far-reaching influence on adjacent landmasses. For example, the wet, warm winds that blow from the ocean to the continental interior in the Pacific Northwest of USA (Chinook wind, in original usage) can raise winter temperature from -20°C to more than +10°C and melt 30 cm or more of snow in a single day. Monsoon systems are another case in point, where seasonal differential heating of a landmass and its nearby ocean cause a reversal of winds from offshore to onshore at the start of the monsoon, often causing torrential rainfall deep into the continental interior.

Despite its critical importance for climatic studies, we have a poor record of ocean heat observations, and it is only since the inception in 2004 of the Argo global network of more than 3,000 ocean profiling probes that we have an adequate estimate of ocean temperatures and heat budget. Though Argo data are in their infancy and subject to

adjustment for errors, early indications are that the oceans are currently cooling (Loehle, 2009).

Shaviv (2008) explored some of the key issues relating to change in ocean heat as a driver of climate change, particularly in response to solar variations. He writes, “climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales,” citing numerous references. Nonetheless, many scientists decline to accept the logical derivative of this fact: Solar variations are driving climate changes. They say measured or reconstructed variations in total solar irradiance (TSI) seem too small to be capable of producing observed climate change.

That concern can be addressed in two ways. The first is to observe that aspects of Earth-sun energy interrelations other than TSI are known to play a role, and perhaps a significant role, in climate change. These mechanisms, addressed in Chapter 3, include:

- Variations in the intensity of the Sun’s magnetic fields on cycles that include the Schwabe (11 year), Hale (22 year), and Gleissberg (70–90-year) periodicities;
- The effect of the sun’s plasma and electromagnetic fields on rates of Earth rotation, and therefore the length of day (LOD);
- The effect of the sun’s gravitational field through the 18.6-year-long Lunar Nodal Cycle, which causes variations in atmospheric pressure, temperature, rainfall, sea level, and ocean temperature, especially at high latitudes;
- The known links between solar activity and monsoonal activity, or the phases of climate oscillations such as the Atlantic Multidecadal Oscillation, a 60-year-long cycle during which sea surface temperature varies $\sim 0.2^\circ\text{C}$ above and below the long-term average, with concomitant effects on Northern Hemisphere air temperature, rainfall and drought; and
- Magnetic fields associated with solar flares, which modulate galactic cosmic ray input into Earth’s atmosphere and in turn may cause variations in the nucleation of low-level clouds at up to a few km high (Ney, 1959; Dickinson, 1975; Svensmark, 1998). This causes cooling, a 1 percent variation in low cloud cover producing a similar change in forcing ($\sim 4\text{ W/m}^2$) as the estimated increase caused by human greenhouse gases. This possible

mechanism is controversial and is being tested in current experiments devised at the European Organization for Nuclear Research (CERN). But irrespective of the results of these experimental tests and of the precise causal mechanism, Neff *et al.* (2001) have provided evidence from palaeoclimate records for a link between varying cosmic radiation and climate (see Figure 6.2.2.1). Using samples from a speleothem from a cave in Oman, Middle East, they found a close correlation between radio-carbon production rates (driven by incoming cosmic radiation, which is solar-modulated) and rainfall (as reflected in the geochemical signature of oxygen isotopes).

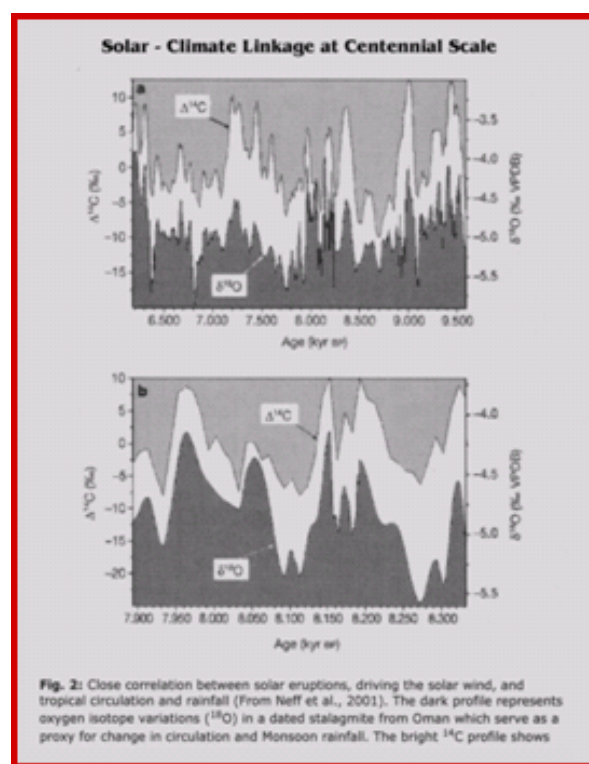


Figure 6.2.2.1. Correlation between proxies for incoming cosmic radiation (radiocarbon production) and rainfall (oxygen isotope signature) from an Oman speleothem. Adapted from Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A. 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411**: 290–293.

- The 1,500-year-long Bond Cycle is probably also of solar origin, and another climate rhythm of similar length, the Dansgaard-Oeschger (D-O) cycle, occurs especially in North Atlantic glacial sediments deposited about 90,000–15,000 years ago.

A second way of resolving the too-weak-TSI dilemma would be the discovery of an amplification mechanism of the weak solar radiation signal. Shaviv (2008) makes a good case for the existence of such an amplifier. Shaviv used the oceans as a calorimeter with which to measure the radiative forcing variations associated with the solar cycle. He studied “three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations, each of which can be used independently to derive the oceanic heat flux.”

Shaviv discovered large variations in oceanic heat content associated with the 11-year solar cycle. In addition, the datasets “consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance.” This clearly implies the existence of an amplification mechanism, although without pointing precisely to what that might be.

References

- Dickinson, R.E. 1975. Solar variability and the lower atmosphere. *Bulletin of the American Meteorological Society* **56**: 1240–1248.
- Loehle, C. 2009. Cooling of the global ocean since 2003. *Energy and Environment* **20**: 101–104.
- Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A. 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411**: 290–293.
- Ney, E.P. 1959. Cosmic radiation and weather. *Nature* **183**: 451.
- Shaviv, N.J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* **113**: 10.1029/2007JA012989.
- Svensmark, H. 1998. Influence of cosmic rays on earth's climate. *Physical Review Letters* **81**: 5027–5030.

6.2.2.1. Ocean Heat Measurement

Ocean heat content is determined by extrapolating vertical temperature and salinity profile data collected by a range of techniques at different sampling densities (Emery and Thomson, 2001). The specific heat of seawater is a complex function of temperature, salinity, and pressure (Fofonoff and Millard Jr., 1983), so all three parameters are required to estimate the heat content within a profile. Due to the high heat

capacity of water ($\sim 4 \text{ kJ.kg}^{-1}.\text{°C}^{-1}$), small changes in temperature result in significant changes in specific heat depending on salinity and pressure (see Figure 6.2.2.1.1). Small errors in temperature measurement thus result in large errors in estimated heat content. This leads to special difficulties in the modern use of older data. Early data obtained by hydrocasts were manually error-checked by comparing the measured profiles with the “expected” or “known” trends, leading Emery and Thomson to comment, “As a matter of curiosity, it would be interesting to determine the number of deep hydrocast data that were unknowingly collected at hydrothermal venting sites and discarded because they were ‘erroneous.’”

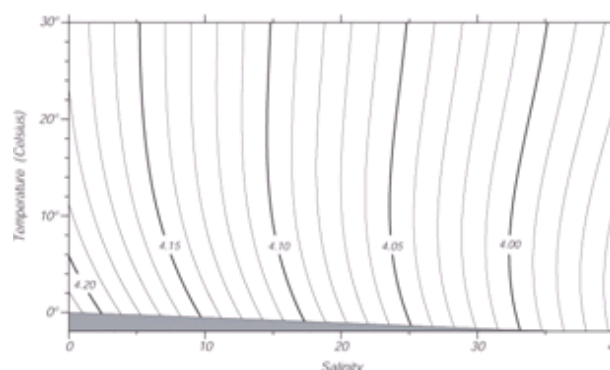


Figure 6.2.2.1.1. Specific heat of seawater in $\text{J.g}^{-1}.\text{°C}^{-1}$ at atmospheric pressure for a typical range of ocean temperatures and salinities. Stuart, Robert H. (2008) *Introduction to Physical Oceanography*. Chapter 5, The Oceanic Heat Budget, Figure 5.1. oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book.pdf.

Deep ocean conditions were measured by hydrocasts using different sensor types lowered and then raised to the surface. Typically the collected data displayed hysteresis³ due to the relatively slow response times of the sensors. Subsequently, profiles were obtained by expendable bathythermographs (XBTs), which measure only a descent profile, or profiling floats that measured descent and ascent profiles in different locations to correct for variable periods of drifting between ascent/descent.

Surface layer temperatures have been measured by buckets, inlet temperatures for engine cooling

³ Data collected during the descent tended to be too warm, and during the ascent too cold. Averaging the two profiles was assumed to give a more reliable estimate of the true conditions.

Observations: The Hydrosphere and Oceans

systems, and thermistor strings suspended from surface buoys. Finally, the skin temperature of the ocean can be estimated from the infrared radiation emitted as observed by satellite or airborne sensors (Emery and Thomson, 2001). This wide range of measurement techniques makes direct comparisons of ocean heat between repeat surveys problematic.

In addition, the sample coverage of the oceans is relatively sparse, particularly before the Argo array of profiling floats achieved near global coverage in 2004. Hence, the measured heat contents are extrapolated over large volumes to estimate the global heat content. This has led some studies to conclude ocean heat can be determined only since 1993 (Lyman *et al.* 2010). Carson and Harrison (2008) demonstrated inferred warming of the ocean was largely a consequence of the data interpolation methodologies used, which tended to be biased toward the 30 percent of the ocean regions that warmed and ignored regions that had cooled.

Quite large variations among even recent studies are evident (Lyman *et al.*, 2010). Willis *et al.* (2009) compare results determined from different data sources over a three-year period (see Figure 6.2.2.1.2). All data taken together indicated cooling; XBT data and estimates from satellite altimetry indicated a slight cooling; and Argo data excluding known faulty floats indicated slight cooling. The faulty Argo floats strongly influenced the results. In addition, the Argo floats found lower ocean heat content than the other data sources. Since the proportion of data derived from Argo floats increased with time, Willis *et al.* suggest the combination of data sources also created a cooling bias.

References

- Carson, M. and Harrison, D.E. 2008. Is the upper ocean warming? Comparisons of 50-year trends from different analyses. *Journal of Climate* **21**: 2259–2268.
- Emery, W.J. and Thomson, R.E.. 2001. *Data analysis methods in physical oceanography* (2nd Edition): Amsterdam, Elsevier.
- Fofonoff, N.P. and Millard Jr., R.C. 1983. Algorithms for computation of fundamental properties of seawater. *Unesco technical papers in marine science* **44** (1983).
- Lyman, J.M., Good, S.A., Gouretski, V.V., Ishii, M., Johnson, G.C., Palmer, M.D., Smith, D.M., and Willis, J.K. 2010. Robust warming of the global upper ocean. *Nature* **465** (7296): 334–337. doi:10.1038/nature09043.
- Stuart, Robert H. (2008) *Introduction to Physical Oceanography*. Chapter 5, The Oceanic Heat Budget,

Figure 5.1. oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book.pdf.

Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852.

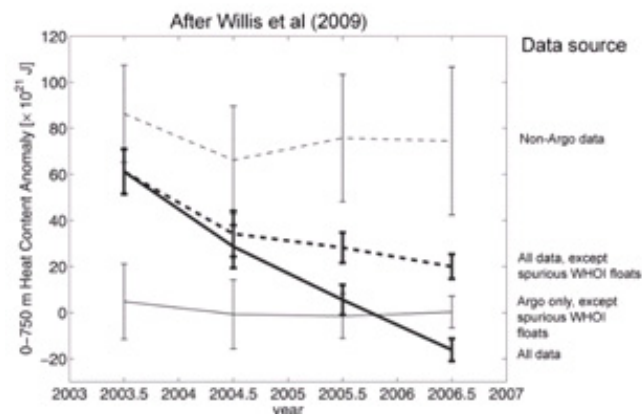


Figure 6.2.2.1.2. Comparison of global ocean heat content changes for the upper 750 m of using different combinations of data sources. Adapted from Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852, Figure 4.

6.2.2.2. Ocean Heat Trends

Willis *et al.* (2009) point out “as the Earth warms due to the buildup of greenhouse gases in the atmosphere, the majority of the excess heat is expected to go toward warming the oceans (Levitus *et al.*, 2005; Hansen *et al.*, 2005).” In contradiction of this expectation, a significant cooling in the ocean heat content anomaly (OHCA) was reported between 2003 and 2005 by Lyman *et al.* (2006).

As discussed in the previous section, Willis *et al.* (2009) concluded the cooling reported by Lyman *et al.* (2006) was an artifact caused by XBT warm bias and Argo cold bias because of the changing proportion of data sources over time. They concluded “OHCA does not appear to exhibit significant warming or cooling between 2003 and 2006.” Willis *et al.* also note the absence of a significant cooling signal in the adjusted OHCA results “brings estimates of upper-ocean thermosteric sea level variability into closer agreement with altimeter-derived measurements of global mean sea level rise.”

Domingues *et al.* (2008) adjusted their estimates of ocean heat content to match sea-level changes as determined by Church and White (2006). The period of analysis, from 1950 to 2003, excludes the Argo data. They found an increase in ocean heat content, mostly between 1970 and 2003, with significant multidecadal oscillations that do not fit volcanic eruptions or ENSO variations well.

Lynman *et al.* (2010) revised their earlier study and incorporated an analysis of uncertainties in other studies by examining the effect of different methodologies used to estimate ocean heat. Their analysis focused on the period 1993 to 2008; they found ocean heat increased over this period, mostly between 2000 and 2002, but there had been negligible changes in ocean heat since 2003.

Katsman and van Oldenburgh (2011a, b) considered the period 2003–2010 and note “the upper ocean has not gained any heat, despite the general expectation that the ocean will absorb most of the Earth’s current radiative imbalance.” Based on an ensemble of climate models, they attributed the lack of any gain in ocean heat to ENSO events resulting in an increased loss of heat to space and increased warming in the ocean depths due to reduced northwards transport of heat in the Atlantic Ocean. This interpretation is difficult to reconcile with the behavior of ocean circulation, and especially its climatic lag effects. For example, it can take almost a decade for the heat generated by an ENSO warm event in the Pacific to travel through the Indian Ocean, around the Cape of Good Hope, and up the Atlantic to feed into the Gulf Stream (see also Section 6.2.3 below).

Gouretski *et al.* (2012) consider ocean heating since 1900, but only for the upper 400 m. They found two distinct warming periods, between 1900 and 1940–1945 and between 1970–2003. They found patterns of heating in the upper 20 m mirrored global temperature patterns and appear to include an 11-year cycle and responses to ENSO events. They also noted a distinct flattening of the ocean heating trend for the twenty-first century.

Comparing the trends determined by Levitus *et al.* for 0–2,000 m and 700–2,000 m shown in Figure 6.2.2.2.1, it is clear the upper 700 m of the ocean is more variable than the lower layer. There is no evidence of an acceleration of warming in the lower layer in the twenty-first century.

Balmaseda *et al.* (2013) attempted to account for the lack of warming in the atmosphere and upper ocean by undertaking a reanalysis of the available data and estimating the total heat content of the ocean

(upper 300 m, upper 700 m, and total water column). Their method involved adjusting numerical model simulations with observational data for the period 1958–2009, which is similar to the period considered by Levitus *et al.* (2012). Balmaseda *et al.* concluded over the final decade 30 percent of the ocean heat content increase occurred below 700 m, and this increase continued despite the hiatus of warming at the surface.

The authors suggest this represents an increase in the rate of warming of the deep ocean. However, as noted by Levitus *et al.* (2012), over the period 1955–2010 about 30 percent of the warming occurred between 700 and 2000 m, indicating the result reported by Balmaseda *et al.* (2013) is not unusual. The reanalysis data produced by Balmaseda *et al.* also show a greater response to volcanic forcing and ENSO events than is evident in observational datasets, suggesting the models may be exaggerating the effect of these processes. Finally, the decadal trends estimated from model results for depths below 700 m (Table 1 of Balmaseda *et al.*, 2013) indicate decadal changes not evident in Figure 6.2.2.2.1.

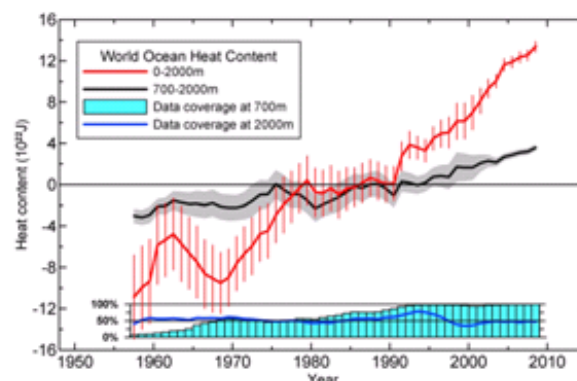


Figure 6.2.2.2.1. Smoothed (pentadal) ocean heat estimates for 0–2000 m and 700–2000 m determined by Levitus *et al.* (2012). The average temperature increases associated with the changed heat contents are 0.09°C and 0.18°C for the top 2000 m and 700 m respectively. Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., and Zweng, M.M. 2012. World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010: *Geophysical Research Letters* **39**: L10603–L10603.

Nuccitelli *et al.* (2012) presented a recalculated estimate of ocean heat content to 2,000 m between 1960 and 2008 (see Figure 6.2.2.2.2). Earlier estimates of OHC cover only the shallow ocean to 700 m and show little of the warming that is apparent

Observations: The Hydrosphere and Oceans

in Figure 6.2.2.2. From their new compilation, Nuccitelli *et al.* conclude global warming is continuing. Their interpretation is at best partially valid, for several reasons.

First, Figure 6.2.2.2 shows warming between 2003 and 2008, when the record ends. This pattern is contradicted by the Argo profiling buoy database, which shows a flatlining or gentle cooling for 2003 to 2008. The Argo conclusion is supported by the available measurements of global sea-surface temperature, which also show cooling since 2000 (see Figure 6.2.2.3).

Second, no error bars are shown in Figure 6.2.2.2, yet they are likely to be greater than the range of change shown even for the post-2003 Argo time period; data before that date are unsystematic,

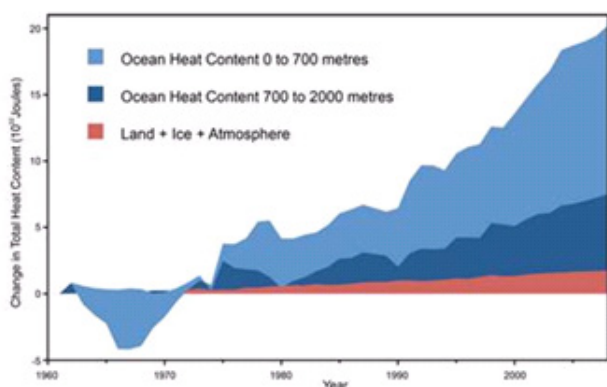


Figure 6.2.2.2. Ocean heat estimates. Nuccitelli, D., Way, R., Painting, R., Church, J., and Cook, J. 2012. Comment on “Ocean heat content and Earth’s radiation imbalance. II. Relation to climate shifts.” *Physics Letters A* **376**: 3466–3468.

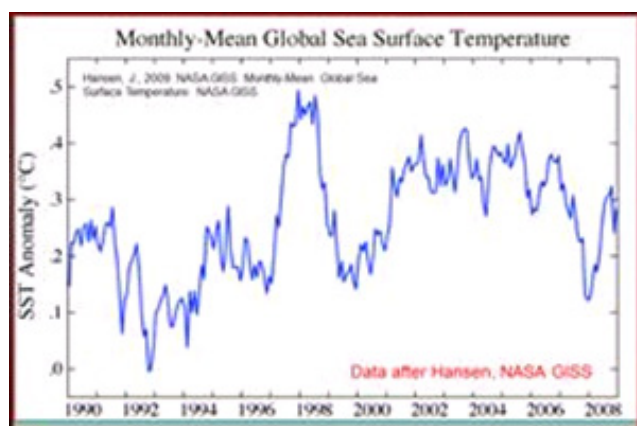


Figure 6.2.2.3. Mean global sea surface temperatures, 1990–2008. NASA 2008. <http://data.giss.nasa.gov/gistemp/2008/>.

with error bars so large the curve depicted is, at best, an educated guess. Third, the mechanisms that transmit incoming heat from the surface to intermediate and deep water masses have time constants of many years to centuries. Even if the depicted upper ocean warming were true, it would represent heat added to the ocean at least many decades if not centuries ago—which means it cannot have been caused by atmospheric CO₂.

Conclusions

At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 15 years or more of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming.

Increasingly, this problem has been finessed by the argument that the atmosphere holds only a small percentage of the world’s heat, and what really counts is the 93 percent of global heat sequestered in the oceans. Yet no sign of significant or accelerated ocean warming exists.

References

- Balmaseda, M.A., Trenberth, K.E., and Källén, E. 2013. Distinctive climate signals in reanalysis of global ocean heat content. *Geophysical Research Letters* (Online May 1): doi:10.1002/grl.50382.
- Church, J.A. and White, N.J. 2006. A 20th century acceleration in global sea-level rise: *Geophysical Research Letters* **33**: L01602: 1–4.
- Domingues, C.M., Church, J.A., White, N.J., Gleckler, P.J., Wijffels, S.E., Barker, P.M., and Dunn, J.R. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* **453** (7198) (June 19): 1090–1093. doi:10.1038/nature07080.
- Gouretski, V., Kennedy, J., Boyer, T., and Köhl, A. 2012. Consistent near-surface ocean warming since 1900 in two largely independent observing networks. *Geophysical Research Letters* **39**: L19606, doi:10.1029/2012GL052975.
- Hansen, J. *et al.* 2005. Earth’s energy imbalance: Confirmation and implications. *Science* **308**: 1431–1451.
- Katsman, C.A. and van Oldenborgh, G.J. 2011a. Tracing the upper ocean’s “missing heat.” *Geophysical Research Letters* **38** (14) (July 1): L14610. doi:10.1029/2011GL048417.
- Katsman, C.A. and van Oldenborgh, G.J. 2011b.

Correction to “Tracing the upper ocean’s ‘missing heat.’”
Geophysical Research Letters **38** (20) (October 1): L20602.
doi:10.1029/2011GL049834.

Levitus, S.J., Antonov, I., and Boyer, T.P. 2005. Warming of the world ocean, 1955–2003. *Geophysical Research Letters* **32**: 10.1029/2004GL021592.

Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., and Zweng, M.M. 2012. World ocean heat content and thermocline sea level change (0–2000 m), 1955–2010: *Geophysical Research Letters* **39**: L10603–L10603.

Lyman, J.M., Good, S.A., Gouretski, V.V., Ishii, M., Johnson, G.C., Palmer, M.D., Smith, D.M., and Willis, J.K. 2010. Robust warming of the global upper ocean. *Nature* **465** (7296): 334–337. doi:10.1038/nature09043.

Lyman, J., Willis, K., and Johnson, G.C. 2006. Recent cooling in the upper ocean. *Geophysical Research Letters* **33**: 10.1029/2006GL027033.

Nuccitelli, D., Way, R., Painting, R., Church, J., and Cook, J. 2012. Comment on “Ocean heat content and Earth’s radiation imbalance. II. Relation to climate shifts.” *Physics Letters A* **376**: 3466–3468.

Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852.

6.2.3. Ocean Circulation

6.2.3.1. The Cenozoic palaeo-ocean

The high specific heat of seawater makes ocean circulation the dominant mechanism for redistributing thermal energy within Earth’s climate system. Zachos *et al.* (2001) summarized the evolution of the global climate over the Cenozoic (last 65 million years) based on data obtained by the DSDP and ODP ocean drilling programmes (see Figure 6.2.3.1.1). It is evident that significant shifts in climate have been associated with major changes in ocean circulation. Major conclusions that can be drawn about ocean history from Figure 6.2.3.1.1, and the supporting references cited in Zachos *et al.* (2001), include the following:

- During the Eocene, the average temperature of the deep ocean declined by more than 7°C from ~12°C during the Eocene climatic optimum to ~4.5°C at the start of the Oligocene. This decline was associated with an increase in marine productivity,

which had fallen after widespread benthic extinctions during the late Paleocene and early Eocene.

- The start of the Oligocene was associated with the opening of the Tasmania-Antarctica Passage between the Australia and Antarctic continents. This was associated with a reduction in the tropical linkages between the Pacific and Indian Oceans (strictly, their equivalents) north of Australia.
- During the Oligocene, the Drake Passage between the South America and Antarctic continents opened, allowing water to circulate around Antarctica and linking all the ocean basins. The change in ocean circulation due to the opening of the two passages was associated with the formation of an Antarctic ice cap and a further drop in deep ocean temperatures.
- The late Oligocene was marked by warming, before temperatures fell during the Miocene.
- At the start of the Pliocene the Panama Seaway between the North and South America continents closed, removing the tropical linkage between the Pacific and Atlantic Oceans. The tropical through-flow between the Pacific and Indian Oceans also was becoming more restricted. This resulted in the establishment of “modern” ocean circulation and is marked by the onset of Northern Hemisphere glaciation.
- The Pliocene and Pleistocene are characterized by glacial/interglacial climatic swings, suggesting the “modern” ocean circulation system makes Earth more sensitive to Milankovitch orbital cycles.

Reference

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/science.1059412.

6.2.3.2. Modern ocean circulation

In simple terms, atmospheric and oceanic circulation systems transport excess heat from the tropics to higher latitudes—from the Equator towards the Poles. However, ocean circulation is constrained by the

Observations: The Hydrosphere and Oceans

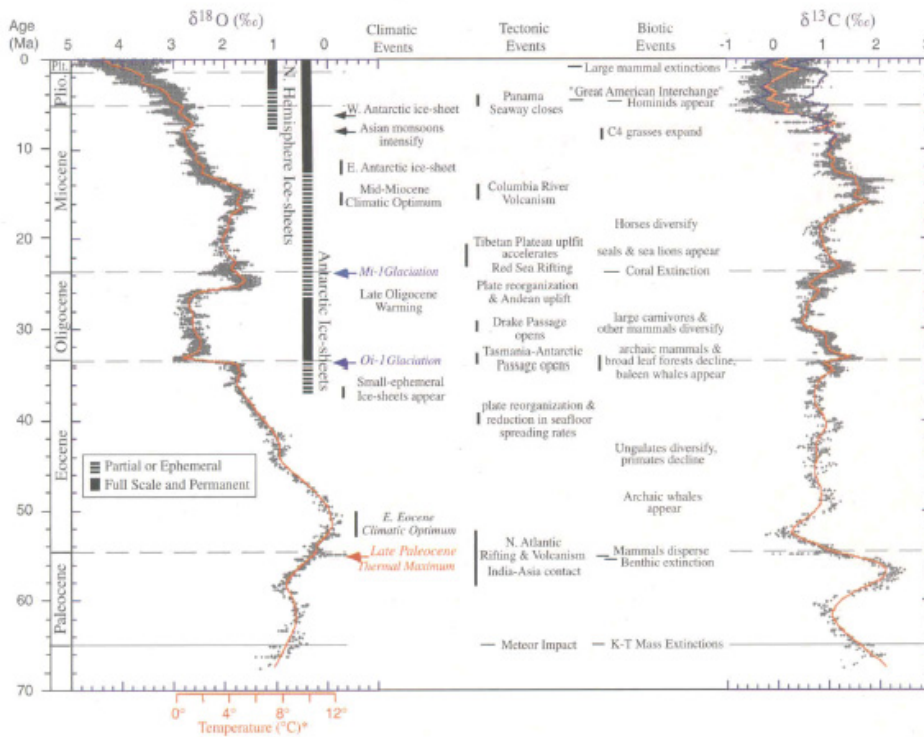


Figure 6.2.3.1.1. Summary of the major climatic, tectonic and biotic events over the last 65 million years correlated with the oxygen and carbon isotope data collected from over 40 DSDP and ODP sediment cores. Reprinted with permission from Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/science.1059412.

configurations of ocean basins and the linkages between them. As discussed in the previous section, major changes in the basin linkages in the past have been associated with significant climatic shifts (Zachos *et al.*, 2001). The current climate is, in part, a product of the modern system of ocean circulation.

There are two main components of circulation: a surface system driven primarily by wind stress exerted by the atmosphere, and a subsurface system driven primarily by density differences associated with variations in temperature and salinity (thermohaline circulation). These two systems are linked by regions where water sinks (downwelling) and rises (upwelling) to provide a complete circulation system that eventually mixes the oceans (overturning).

A popular simplification of the combined global overturning circulation is known as the Great Ocean Conveyor Belt (see Figure 6.2.3.2.1), which emphasizes the downwelling of water in the North Atlantic to drive the thermohaline circulation and the overall transport of water back into the North Atlantic by the surface circulation driving upwelling in the

Indian and Pacific Oceans (Broecker, 1991). Broecker (1997) used this concept to argue global warming could trigger abrupt climate change by slowing or stopping the downwelling of water in the North Atlantic.

The flows depicted in Figure 6.2.3.2.1, however, are unrealistic: the surface heat transport in the North Pacific is in the wrong direction, and the Indonesian through-flow is exaggerated. Schmitz (1996) presented a different version of the Great Ocean Conveyor Belt summarizing the known circulation components and their volume transport rates (see Figure 6.2.3.2.2, page 805). This diagram is difficult to conceptualize, so he prepared a perspective diagram to illustrate the relationships (see Figure 6.2.3.2.3).

Although the ocean basins are linked by circulation around Antarctic and some through-flow through the Arctic and the Indonesian Archipelago, it is evident there is also significant overturning circulation within each ocean basin. Schmitz (1996) refers to this basinal circulation as consisting of meridional overturning circulation cells.

With the exception of the South Atlantic Ocean, the cells tend to involve a net transport of warm water away from the Equator at the surface and cold water towards the Equator at depth. The South Atlantic cells produce a net transport of warm water towards the Equator, adding to the transport of warm water to the North Atlantic. Overall, there is an extra 0.5 PW (petawatt = 10^{15} W) of thermal energy transported to the North Atlantic Ocean compared to the North Pacific Ocean. This extra energy is transferred to the atmosphere as latent heat through evaporation, resulting in saltier (warm) water, which sinks and drives thermohaline circulation.

To balance the water losses associated with increased evaporation in the North Atlantic, there is increased precipitation over the North Pacific,

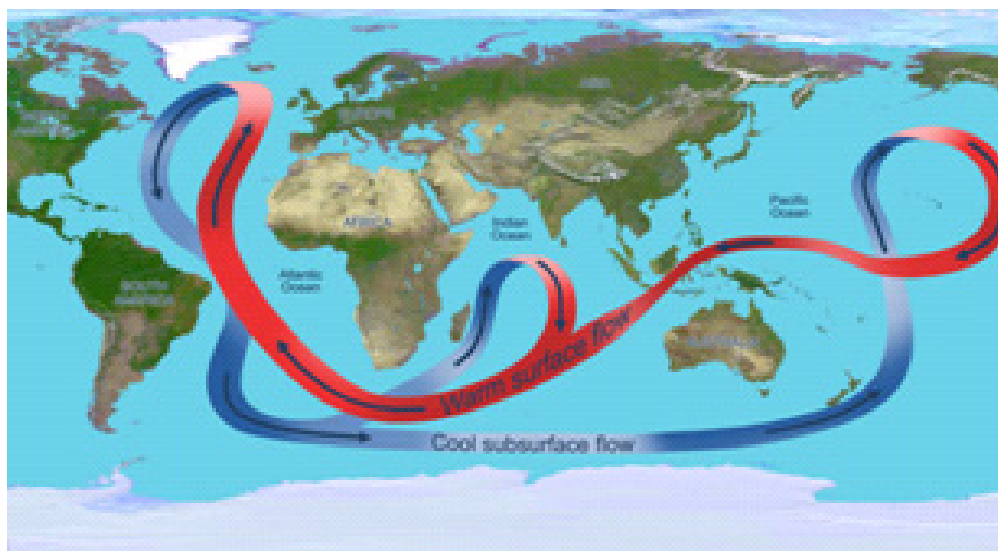


Figure 6.2.3.2.1. Simplified ocean circulation system known as the Great Ocean Conveyor Belt, highlighting the net transport of heat to the North Atlantic by surface circulation. (<http://www.jpl.nasa.gov/images/earth/20100325/atlantic20100325-full.jpg>).

resulting in fresher (cold) water. The component of this water that flows into the Arctic is comparatively easier to freeze than the saltier water from the North Atlantic, favoring ice formation in the Chukchi Sea over the Barents Sea.

Conclusions

Clearly, fluctuations in the supply of excess thermal energy to the North Atlantic and other oceans will have climatic consequences, and some past changes in the flow of the global ocean circulation system can be shown to be linked to major climate change; for example, flow speeds of the cold-water Pacific Deep Western Boundary Current increased during past glacial periods (Hall *et al.*, 2001). The IPCC, noting such facts, argues global warming will change the speed of major ocean circulation phenomena such as the Gulf Stream in ways that will make the world's climate less hospitable. To date, however, no published evidence exists for changes in the ocean thermohaline circulation system that lie outside the bounds of natural variation.

References

- Broecker, W.S. 1991. The great ocean conveyor. *Oceanography* 4: 79–89.
- Broecker, W.S. 1997. Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO₂ upset the current balance? *Science* 278: 1582–1588.

Hall, I.R., McCave, I.N., Shackleton, N.J., Weedon, G.P., and Harris, S.E. 2001. Glacial intensification of deep Pacific inflow and ventilation. *Nature* 412: 809–811.

Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* 292 (5517): 686–693. doi:10.1126/science.1059412.

6.2.3.3. Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) consists of a near-surface, warm northward flow in the Atlantic Ocean compensated by a colder southward return flow at depth (Srokosz *et al.*, 2012). A key feature is the transfer of heat to the atmosphere at high latitudes in the North Atlantic, which makes the northward-flowing surface waters saltier and cooler (denser), causing them to sink to considerable depths.

Srokosz *et al.* (2012) provide a schematic illustration of the main flows of AMOC (see Figure 6.2.3.3.1, page 806). Similar to the Great Ocean Conveyor Belt, this schematic oversimplifies the components of the circulation cell. Figure 6.2.3.3.2

Observations: The Hydrosphere and Oceans

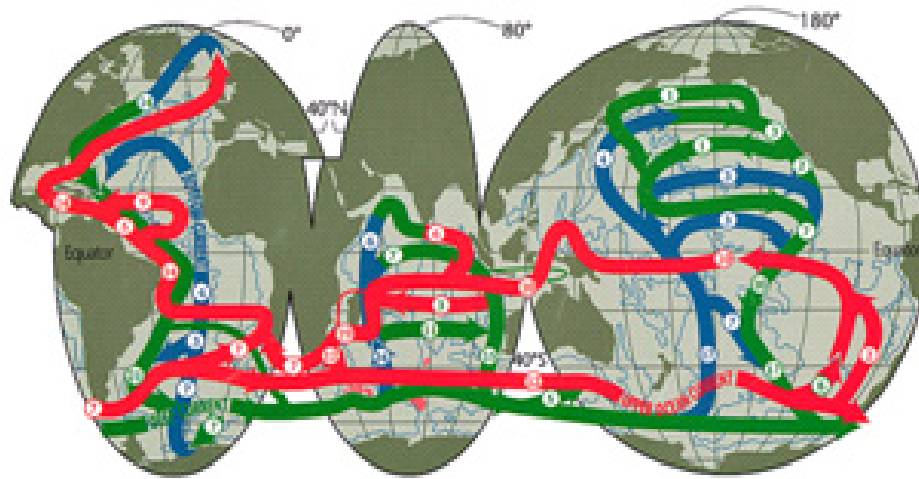


Figure 6.2.3.2.2. Summary of the main components of global ocean circulation. The volume transport rates in Sverdrups ($1 \text{ Sv} = 106 \text{ m}^3 \cdot \text{s}^{-1}$) are indicated in the circles. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

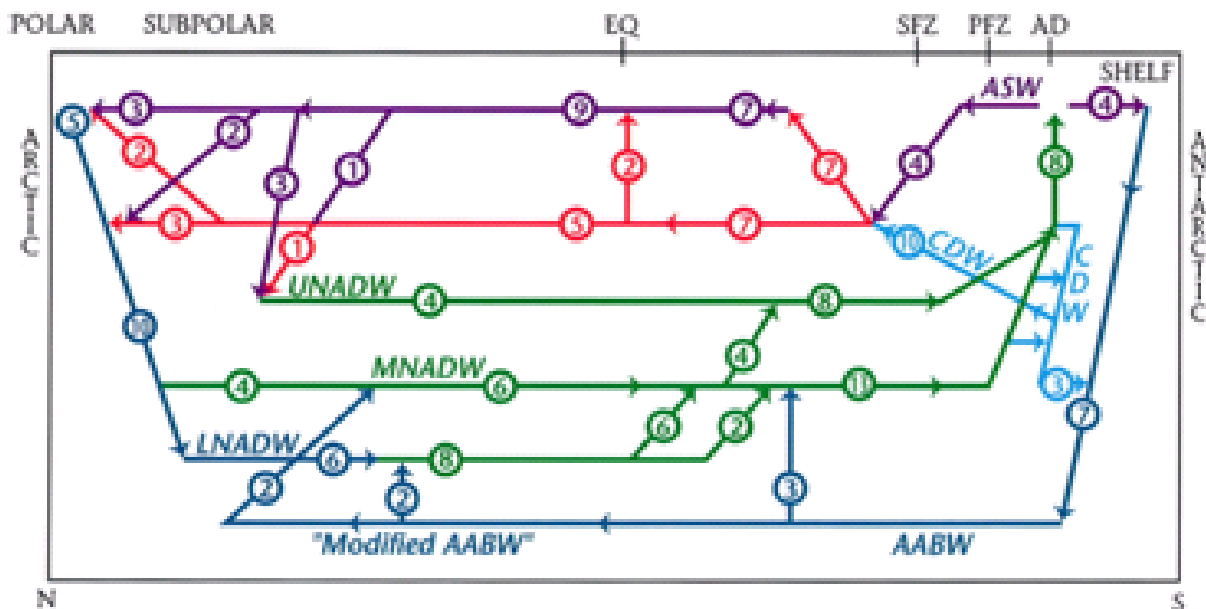


Figure 6.2.3.2.3. Components of AMOC at different depths within the Atlantic, where purple denotes an upper layer, red indicates intermediate water, green deep water, dark blue bottom, and light blue represents Circumpolar Deep Water (Schmitz, 1996). The volume transport rates for each limb are given in Sverdrups.

(on page 807), originally presented by Schmitz (1996), summarizes the major components of the circulation contributing to AMOC. This figure illustrates the deeper thermohaline circulation is also driven by water sinking around Antarctica, which means the strength of the circulation is not solely a

function of the formation of dense water in the North Atlantic. There are multiple flow paths at different depths, meaning there are many different lags associated with the circulation of water masses within the system.

Baehr *et al.* (2007, 2008) used modeling to



Figure 6.2.3.3.1. Simplified model of the AMOC that regulates northern Hemisphere climate. Reprinted with permission from Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delworth, T., Lozier, S., Marotzke, J., and Sutton, R. 2012. Past, present, and future changes in the Atlantic Meridional Overturning Circulation. *Bulletin of the American Meteorological Society* **93**(11): 1663–1676. doi:10.1175/BAMS-D-11-00151.1.

assess how quickly changes in the North Atlantic meridional overturning circulation (MOC) might flow through into consequential climate change. Simulated observations were projected onto a time-independent spatial pattern of natural variability. This variability was derived by regressing the zonal density gradient along 26°N against the strength of the MOC at 26°N, within a model-based control climate simulation. The resultant pattern was compared against observed anomalies found between the 1957 and 2004 hydrographic occupations of this latitudinal section.

The modeling revealed Atlantic MOC changes could be detected with 95% reliability after about 30 years, manifest by changes in zonal density gradients obtained from a recently deployed monitoring array. In terms of potential past changes Baehr *et al.* found “for the five hydrographic occupations of the 26°N transect, none of the analyzed depth ranges shows a significant trend between 1957 and 2004, implying that there was no MOC trend over the past 50 years.”

This finding demonstrates the mild late twentieth century warming that so alarms the IPCC has not resulted in any observable change in the North Atlantic MOC. In turn, this suggests the North Atlantic MOC is not nearly as sensitive to global warming as many climate models employed by the IPCC suggest.

In a second paper addressing North Atlantic deep water formation and circulation, Vage *et al.* (2008) write, “in response to global warming, most climate models predict a decline in the Meridional Overturning Circulation, often due to a reduction of Labrador Sea Water,” noting “since the mid-1990s, convection in the Labrador Sea has been shallow—and at times nearly absent.”

Vage *et al.*’s paper uses Argo data, supplemented by satellite and reanalysis data, to document a return of deep convection to the subpolar gyre in both the Labrador and Irminger seas in the winter of 2007–2008. Winter mixing was observed to depths of 1,800 m in the Labrador Sea, 1,000 m in the Irminger Sea, and 1,600 m south of Greenland, whereas base-period (the winters of 2001–2006) mixing depths were less than 1,000 m. By analyzing heat flux components, Vage *et al.* determined the main cause of the enhanced heat flux and deep mixing was unusually cold air temperatures during the 2007–2008 winter. Moreover, the cooling was not merely a local phenomenon; global temperature dropped 0.45°C between the winters of 2006–2007 and 2007–2008.

Srokosz *et al.* (2012) provide a review of available research on AMOC and associated climatic variations. They highlight how poorly understood the system is; the lack of key time series data, particularly for the deeper components of AMOC; and the poor predictive abilities of computer models. From the available data, they demonstrate the recent behavior of AMOC has been surprising and unexplainable. They conclude AMOC plays a major role in climate changes, there is an urgent need for better observational data, and the behavior and potential predictability of the system need further study.

Conclusions

Studies of various parts of the global thermohaline circulation show flow rates can be quite widely variable. This variability has natural causes that have yet to be identified fully. Meanwhile, no evidence exists for additional change in ocean circulation forced by human carbon dioxide emissions.

References

- Baehr, J., Keller, K., and Marotzke, J. 2008. Detecting potential changes in the meridional overturning circulation at 26°N in the Atlantic. *Climatic Change* **91**: 11–27.
- Baehr, J., Haak, H., Alderson, S., Cunningham, S.A., Jungclaus, J.H., and Marotzke, J. 2007. Timely detection of changes in the meridional overturning circulation at 26°N in the Atlantic. *Journal of Climate* **20**: 5827–5841.

Observations: The Hydrosphere and Oceans

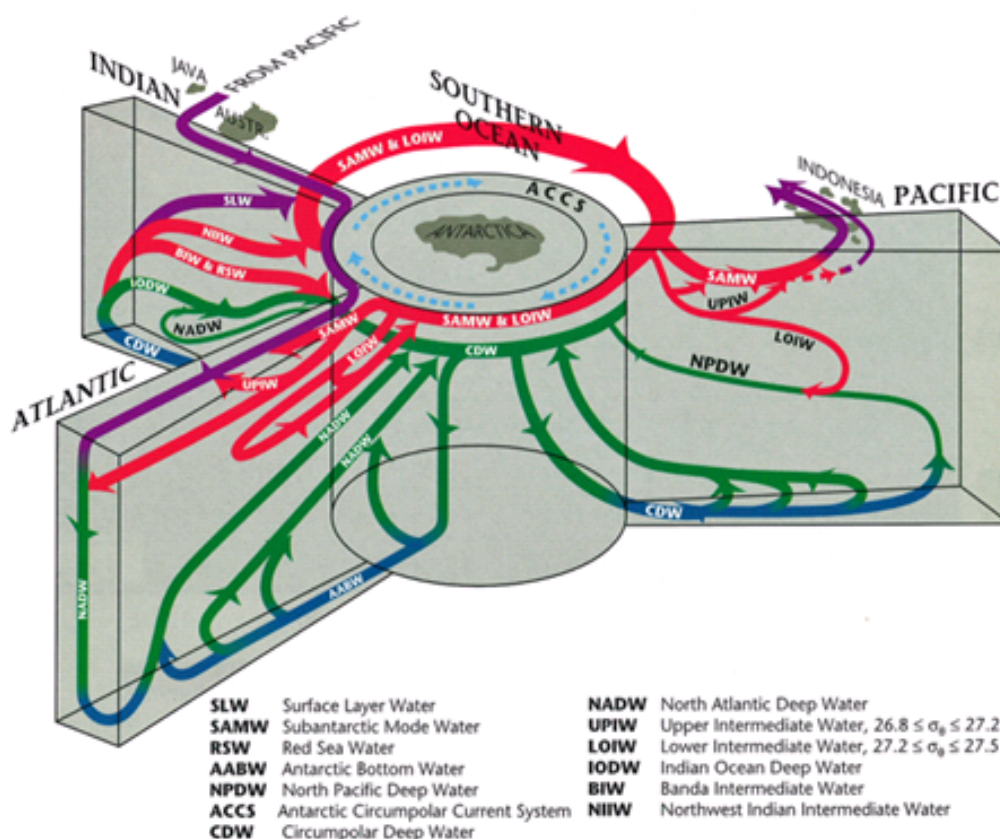


Figure 6.2.3.2. Summary of the main components of the global ocean circulation system. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delworth, T., Lozier, S., Marotzke, J., and Sutton, R. 2012. Past, present, and future changes in the Atlantic Meridional

Overturning Circulation. *Bulletin of the American Meteorological Society* **93**(11): 1663–1676. doi:10.1175/BAMS-D-11-00151.1.

Vage, K., Pickart, R.S., Thierry, V., Reverdin, G., Lee, C.M., Petrie, B., Agnew, T.A., Wong, A., and Ribergaard, M.H. 2008. Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007–2008. *Nature Geoscience* **2**: 67–72.

7

Observations: Extreme Weather

Madhav Khandekar (Canada)

Craig Idso (USA)

Key Findings

Introduction

7.1 Temperature

- 7.1.1 Asia
- 7.1.2 Europe
- 7.1.3 North America
- 7.1.4 Other Areas
- 7.1.5 Cold Weather Extremes

7.2 Heat Waves

7.3 Fire

7.4 Drought

- 7.4.1 Africa
- 7.4.2 Asia
- 7.4.3 Europe
- 7.4.4 North America
- 7.4.6 Global

7.5 Floods

- 7.5.1 Africa
- 7.5.2 Asia

7.5.3 Europe

7.5.4 North America

7.5.5 South America

7.6 Precipitation

7.6.1 Africa

7.6.2 Asia

7.6.3 Europe

7.6.4 North America

7.7 Storms

7.7.1 Regional Trends

7.7.2 Dust Storms

7.7.3 Hail

7.7.4 Tornadoes

7.7.5 Wind

7.8 Hurricanes

7.8.1 Atlantic Ocean

7.8.2 Indian Ocean

7.8.3 Pacific Ocean

7.8.4 Global

Key Findings

The following points summarize the main findings of this chapter:

- Air temperature variability decreases as mean air temperature rises, on all time scales.
- Therefore the claim that global warming will lead

to more extremes of climate and weather, including of temperature itself, seems theoretically unsound; the claim is also unsupported by empirical evidence.

- Although specific regions have experienced significant changes in the intensity or number of extreme events over the twentieth century, for the globe as a whole no relationship exists between

such events and global warming over the past 100 years.

- Observations from across the planet demonstrate droughts have not become more extreme or erratic in response to global warming. In most cases, the worst droughts in recorded meteorological history were much milder than droughts that occurred periodically during much colder times.
- There is little or no evidence that precipitation will become more variable and intense in a warming world; indeed, some observations show just the opposite.
- There has been no significant increase in either the frequency or intensity of stormy weather in the modern era.
- Despite the supposedly “unprecedented” warming of the twentieth century, there has been no increase in the intensity or frequency of tropical cyclones globally or in any of the specific ocean basins.

Introduction

For more than two decades the United Nations Intergovernmental Panel on Climate Change (IPCC) has supported the model-based narrative that carbon dioxide (CO₂)-induced global warming will cause (or is already causing) extreme weather, including more frequent and more severe heat waves, precipitation extremes (droughts and floods), storms, tropical cyclones, and other extreme weather-related events. With respect to observed changes in extreme weather, the 2012 IPCC special report on extreme weather (Field *et al.*, 2012) states:

There is evidence from observations gathered since 1950 of change in some extremes. Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning ‘low confidence’ in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme.

With respect to projected changes in extreme weather, that special report states:

Confidence in projecting changes in the direction and magnitude of climate extremes depends on many factors, including the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models. ... Assigning ‘low confidence’ for projections of a specific extreme neither implies nor excludes the possibility of changes in this extreme.

Chapter 1 of this NIPCC report presents evidence the climate models are fraught with numerous biases and shortcomings that lead to significant errors in their projections, leaving model projections highly questionable at best. Such a conclusion is especially true for projections of extreme weather events, which are much more difficult to model than average conditions and operate on much larger spatial and temporal scales. Because the models were critically examined in Chapter 1, the evaluation of their extreme weather projections will be of minor focus here. Instead, the majority of material presented in this chapter focuses on empirical observations.

More specifically, this chapter reviews historical trends in extreme weather events and examines how they interrelate with other weather and climate variables. It is clear in almost every instance of each extreme weather event examined, there is little support for predictions that CO₂-induced global warming will increase either the frequency or intensity of those events. The real-world data overwhelmingly support an opposite conclusion: Weather will more likely be less extreme in a warmer world.

References

- Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., and Midgley, P.M. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.
- IPCC 2007-I. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Cambridge University Press, Cambridge, UK.

7.1 Temperature

One of the projected negative consequences of global warming is an increase in climatic variability, including more frequent extreme temperatures (mainly at the warm end of the temperature spectrum). The IPCC's *Fifth Assessment Report* claims more evidence now exists that "the AR4 conclusion that surface temperature extremes have likely been affected by anthropogenic forcing" is correct, adding "we now conclude that it is very likely that anthropogenic forcing has contributed to the observed changes in temperature extremes since the mid-20th century" (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, model projections suggest these extreme events will increase throughout this century as a consequence of CO₂-induced global warming.

It is a relatively easy matter to either substantiate or refute such claims by examining trends of extreme temperatures over the past century or so. If global warming truly has been occurring at an unprecedented rate over the past hundred years and global warming causes an increase in extreme weather events, as often claimed, temperature variability and extreme temperature events should be increasing. In the subsections of Section 7.1 that follow, we investigate this topic as it pertains to locations in Asia (7.1.1), Europe (7.1.2), North America (7.1.3), and Other Areas across the globe (7.1.4). Specifically, we present the findings of many peer-reviewed papers that do not support the IPCC claims in regard to temperature extremes.

Contrary to model projections, the studies referenced in this section indicate a warmer climate does not produce a more variable climate. The data presented herein suggest a warmer climate may very well be less variable and less extreme, if any change occurs at all. Projections of more frequent and more intense temperature extremes do not appear to be supported by the majority of scientific observations as reported in the peer-reviewed literature.

7.1.1 Asia

This subsection highlights several peer-reviewed studies from Asia that do not support the IPCC-based claim that CO₂-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Yadav *et al.* (2004) obtained a long tree-ring series from widely spaced Himalayan cedar trees in an effort to develop a temperature history of the western Himalayas for the period AD 1226–2000. "Since the 16th century," they write, "the

reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226–1500), reflecting unstable climate during the Little Ice Age (LIA)." They note juniper tree-ring chronologies from central Tibet provide similar results (Braeuning, 2001) and "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." In a study of the winter half-year temperatures of a large part of China, Ge *et al.* (2003) identified greater temperature anomalies during the 1600s than in the 1980s and 1990s. Zhang and Gaston (2004) report an even greater extreme anomaly occurred in China in the summer of 1743.

This eighteenth century "heat wave attack" was felt throughout northern China, including Beijing, Tianjin, and the provinces of Hebei, Xhanxi, and Shandong. One report from Tianjin at the time said "July's heat is insupportable; fields full of cracks; rocks scorched; melting metal on mast top; many died of heat." In Gaoyi the temperature was said to be "as hot as fire in rooms and under heavy shades of trees, with melting lead and tin at midday and many died of thirst on 19–26 July." Shenze, Changzhi, Fushan, Gaoqing, and Pingyuan reported people dying from the intense heat, with the communication from Shenze saying "the disaster is indeed unprecedented." Officials reported 11,400 people died from the heat in Beijing and its suburbs between July 14 and July 25. That was a vast underestimate of the real death toll, for it included only "poor people, like craftsmen, or workers," neglecting the deaths of "the well-off and the ones in service," of which "there were a large number." And that was the death toll in the Beijing area alone.

Just how unusual was this deadly heat wave? According to Zhang and Gaston (2004), it was the hottest period of the hottest summer experienced in north China during the past seven centuries, where peak warmth exceeded the modern-day extreme heat wave high temperature by 2°C. It occurred in 1743, sandwiched between two of the coldest intervals of the Little Ice Age, as opposed to occurring during the modern era with its more-precise instruments for measuring temperature and other weather elements.

Focusing in on the modern era, Zhai and Pan (2003) derived trends in the frequencies of warm days and nights, cool days and nights, and hot days and frost days for the whole of China over the period 1951–1999, based on daily surface air temperature data obtained from approximately 200 weather observation stations scattered throughout the country.

Over the period of study, and especially throughout the 1980s and 1990s, the authors found increases in the numbers of warm days and nights, and there were decreases in the numbers of cool days and nights, consistent with an overall increase in mean daily temperature. Nevertheless, at the extreme hot end of the temperature spectrum, the authors report “the number of days with daily maximum temperature above 35°C showed a slightly decreasing trend for China as a whole.” At the extreme cold end of the spectrum, the number of frost days with daily minimum temperature below 0°C declined at the rate of 2.4 days per decade. The data from approximately 200 locations across China reveal during the second half of the twentieth century there was a reduction in extreme cold weather events without any concomitant increase in extreme hot weather.

Zhou and Ren (2011) evaluated trends in 15 extreme temperature indices for the period 1961–2008 using daily temperature records from 526 measurement stations included among the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration. Based on the earlier findings of Zhou and Ren (2009)—which indicated the contribution of urban warming to overall warming often exceeded 50%—they adjusted their results to account for the impact of each site’s urban heat island effect.

Zhou and Ren discovered “urbanization intensified the downward trend in cold index series and the upward trend in warm indices related to minimum temperature.” They report “the urbanization effect on the series of extreme temperature indices was statistically significant for the downward trends in frost days, daily temperature range, cool nights, and cool days,” as well as for “the upward trends in summer days, tropical nights, daily maximum temperature, daily minimum temperature, and warm nights.” For these indices, they state “the contributions of the urbanization effect to the overall trends ranged from 10 to 100%, with the largest contributions coming from tropical nights, daily temperature range, daily maximum temperature and daily minimum temperature,” adding “the decrease in daily temperature range at the national stations in North China was caused entirely by urbanization.” The two researchers concluded, “more attention needs to be given to the issue [of urbanization on temperature] in future studies,” something IPCC contributors and reviewers need to look at much more closely in the future than they have in the past. The

urban influence can explain up to 100% of the change in extreme temperatures over the past half-century in many locations, leaving little or no room for any other influence, including CO₂-induced global warming.

Deng *et al.* (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 obtained from 10 meteorological stations to determine the number of hot days (HDs, at or above 35°C), very hot days (VHDs, at or above 38°C), and extremely hot days (EHDs, at or above 40°C) in an effort to address temperature extremes within the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. They defined a heat wave (HW) as a period with no fewer than three consecutive HDs, a short heat wave (SHW) as being at least six days long, and a long heat wave (LHW) as a heat wave exceeding six days.

Between 1958 and 2007, the three Chinese researchers reported, their study area experienced a mean annual warming trend, but with slight decreasing trends in spring and summer temperatures. Extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that “the frequencies of HWs and LHWs in the recent years were no larger than the late 1950s and early 1960s.” They indicated “coupled with the extreme low frequency in the 1980s, HWs and LHWs showed a slight linear decreasing trend in the past 50 years.” They found the most recent frequency of heat waves “does not outnumber 1959 or 1961,” and “none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003.”

Deng *et al.* conclude, “compared with the 1950s and 1960s, SHWs instead of LHWs have taken place more often,” which, as they describe it, “is desirable, as longer duration leads to higher mortality,” citing Tan *et al.* (2007). For the Three Gorges area of China, even a mean annual warming trend over the past half-century has not led to an increase in the frequency of extremely long heat waves.

References

- Braeuning, A. 2001. Climate history of Tibetan Plateau during the last 1000 years derived from a network of juniper chronologies. *Dendrochronologia* 19: 127–137.
- Deng, H., Zhao, F., and Zhao, X. 2012. Changes of extreme temperature events in Three Gorges area, China.

Environmental and Earth Sciences **66**: 1783–1790.

Ge, Q., Fang, X., and Zheng, J. 2003. Quasi-periodicity of temperature changes on the millennial scale. *Progress in Natural Science* **13**: 601–606.

Tan, J., Zheng, Y., Song, G., Kalkstein, L.S., Kalkstein, A.J., and Tang, Z.X. 2007. Heat wave impacts on mortality in Shanghai, 1998 and 2003. *International Journal of Biometeorology* **51**: 193–200.

Yadav, R.R., Park, W.K., Singh, J., and Dubey, B. 2004. Do the western Himalayas defy global warming? *Geophysical Research Letters* **31**: 10.1029/2004GL020201.

Zhai, P. and Pan, X. 2003. Trends in temperature extremes during 1951–1999 in China. *Geophysical Research Letters* **30**: 10.1029/2003GL018004.

Zhang, D. 2000. *A Compendium of Chinese Meteorological Records of the Last 3000 Years*. Jiangsu Education Press, Nanjing, pp. 2340–2366.

Zhang, D. and Gaston, D. 2004. Northern China maximum temperature in the summer of 1743: A historical event of burning summer in a relatively warm climate background. *Chinese Science Bulletin* **49**: 2508–2514.

Zhang, J. and Crowley, T.J. 1989. Historical climate records in China and reconstruction of past climates (1470–1970). *Journal of Climate* **2**: 833–849.

Zhou, Y.Q. and Ren, G.Y. 2009. The effect of urbanization on maximum and minimum temperatures and daily temperature range in North China. *Plateau Meteorology* **28**: 1158–1166.

Zhou, Y.Q. and Ren, G.Y. 2011. Change in extreme temperature event frequency over mainland China, 1961–2008. *Climate Research* **50**: 125–139.

7.1.2 Europe

This subsection highlights several peer-reviewed studies from Europe that do not support the IPCC-based claim that CO₂-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Beginning with a historic view of the topic, the study of Jones and Briffa (2006), in their words, focused “on one of the most interesting times of the early instrumental period in northwest Europe (from 1730–1745), attempting to place the extremely cold year of 1740 and the unusual warmth of the 1730s decade in a longer context.” The authors relied primarily on “long (and independent) instrumental records together with extensive documentary evidence,” as well as “unpublished subjective

circulation charts developed by the late Hubert Lamb” and “others recently developed using more objective modern reconstruction techniques.”

According to the two researchers from the Climatic Research Unit of the University of East Anglia, the analysis revealed “the period 1740–1743 has been shown to be the driest period of the last 280 years, with the year 1740 the coldest recorded over the British Isles since comparable records began in 1659.” They note the record cold of 1740 “is all the more remarkable given the anomalous warmth of the 1730s,” which was “the warmest in three of the long temperatures series (Central England Temperature, De Bilt and Uppsala) until the 1990s occurred.”

In discussing their findings, Jones and Briffa state their study “highlights how estimates of natural climatic variability in this region based on more recent data may not fully encompass the possible known range” and “consideration of variability in these records from the early 19th century, therefore, may underestimate the range that is possible.” The instrumental record is simply not long enough to provide a true picture of natural temperature variability in terms of what is possible in the absence of the influence of anthropogenic greenhouse gases.

Manrique and Fernandez-Cancio (2000) employed a network of approximately 1,000 samples of tree-ring series representative of a significant part of Spain to reconstruct thousand-year chronologies of temperature and precipitation. They used the database to identify anomalies in these parameters that varied from their means by more than four standard deviations. They found the greatest concentration of extreme climatic excursions, which they describe as “the outstanding oscillations of the Little Ice Age,” occurred between AD 1400 and 1600, during a period when extreme low temperatures reached their maximum frequency.

Focusing on the past century, Rebetez (2001) analyzed day-to-day variability in two temperature series from Switzerland over the period 1901–1999, during which the two sites experienced temperature increases of 1.2 and 1.5°C. Their work revealed warmer temperatures led to a reduction in temperature variability at both locations. They found “warmer temperatures are accompanied by a general reduction of variability, both in daily temperature range and in the monthly day-to-day variability,” indicating even on a much finer time scale, cooling rather than warming brings an increase in temperature variability.

Beniston and Goyette (2007) noted “it has been assumed in numerous investigations related to

climatic change that a warmer climate may also be a more variable climate (e.g., Katz and Brown, 1992; IPCC, 2001; Schar *et al.*, 2004)” and “such statements are often supported by climate models results, as for example in the analysis of GCM and/or RCM simulated temperature and precipitation (Mearns *et al.*, 1995; Mearns *et al.*, 1990).” Therefore, they observed, “it is of interest to investigate whether, based on long time-series of observational data, this hypothesis is indeed verified in a climate that has experienced a warming of 2°C or more.”

Noting twentieth-century warming in the alpine area of Europe “is 2–3 times greater than the global average (Jungo and Beniston, 2001) and provides an observational framework that makes it possible to address the issue of links between mean temperature and its variance,” Beniston and Goyette focused their analysis on one Swiss site representative of low elevation (Basel, 369 m above sea level) and another Swiss site representative of high elevation (Saentis, 2500 m above sea level), both of which “have proven their quality in a number of previous studies (Jungo and Beniston, 2001; Beniston and Jungo, 2002; Beniston and Stephenson, 2004; Beniston and Diaz, 2004),” where they say it was determined conclusions based on data from these sites “also apply to most of the other Swiss sites.”

Beniston and Goyette reported observational data since 1900 at both the low- and high-elevation sites indicate “the inter-annual and decadal variability of both maximum and minimum daily temperatures has in fact *decreased* [emphasis in the original] over the course of the 20th century despite the strong warming that has been observed in the intervening period.” These findings, they added, “are consistent with the temperature analysis carried out by Michaels *et al.* (1998), where their results also do not support the hypothesis that temperatures have become more variable as global temperatures have increased during the 20th century.” In addition, they found “the principal reason for this reduction in variability is related to the strong increase in the persistence of certain weather patterns at the expense of other types.” Thus, the Swiss researchers reported their observations show “contrary to what is commonly hypothesized, climate variability does not necessarily increase as climate warms.” They emphasized “the variance of temperature has actually decreased in Switzerland since the 1960s and 1970s at a time when mean temperatures have risen considerably.”

Chase *et al.* (2006) noted much was made of the supposed uniqueness of the summer of 2003

European heat wave, its implied connection to CO₂-induced global warming, and the proposal that it was evidence of a climatic regime shift to one of greater variability that supports the more frequent occurrence of more extreme warm events (Schar *et al.*, 2004; Stott *et al.*, 2004; Trigo *et al.*, 2005). The group of four researchers utilized NCEP global reanalysis data for the period 1979–2003 to calculate extreme tropospheric temperature events over the region 22°N to 80°N throughout the June–July–August period (and globally using annual averages), after which they compared the results with the corresponding particulars of the European heat wave of 2003 in terms of “standard deviations exceeded and correlations between regional extremes and temperatures at larger spatial scales.”

Their analysis revealed “extreme warm anomalies equally, or more, unusual than the 2003 heat wave occur regularly,” “extreme cold anomalies also occur regularly and can exceed the magnitude of the 2003 warm anomaly,” “warmer than average years have more regional heat waves and colder than average years have more cold waves,” “natural variability in the form of El Niño and volcanism appears of much greater importance than any general warming trend in causing extreme regional temperature anomalies,” and “regression analyses do not provide strong support for the idea that regional heat or cold waves are significantly increasing or decreasing with time during the period considered here.”

Chase *et al.* conclude their analysis “does not support the contention that similar anomalies as seen in summer 2003 are unlikely to recur without invoking a non-stationary statistical regime with a higher average temperature and increased variability.” In other words, the 2003 European summer heat wave implies nothing at all about CO₂-induced global warming. It was merely a rare, but not unprecedented, weather event, of which there have been several other examples (both hot and cold, and some stronger) over the past quarter-century.

In another study conducted in an effort to understand the significance of a modern heat wave from an historical perspective, Dole *et al.* (2011) observed “the 2010 summer heat wave in western Russia was extraordinary, with the region experiencing the warmest July since at least 1880 and numerous locations setting all-time maximum temperature records.” They noted “questions of vital societal interest are whether the 2010 Russian heat wave might have been anticipated, and to what extent human-caused greenhouse gas emissions played a

role.”

Dole *et al.* used climate model simulations and observational data “to determine the impact of observed sea surface temperatures, sea ice conditions and greenhouse gas concentrations.” The nine U.S. researchers found “analysis of forced model simulations indicates that neither human influences nor other slowly evolving ocean boundary conditions contributed substantially to the magnitude of the heat wave.” They observed the model simulations provided “evidence that such an intense event could be produced through natural variability alone.” Similarly, they stated “July surface temperatures for the region impacted by the 2010 Russian heat wave show no significant warming trend over the prior 130-year period from 1880–2009.” They noted “a linear trend calculation yields a total temperature change over the 130 years of -0.1°C .” In addition, they observed “no significant difference exists between July temperatures over western Russia averaged for the last 65 years (1945–2009) versus the prior 65 years (1880–1944)” and “there is also no clear indication of a trend toward increasing warm extremes.” Finally, although there was a slightly higher variability in temperature in the latter period, the increase was “not statistically significant.”

“In summary,” Dole *et al.* observed, “the analysis of the observed 1880–2009 time series shows that no statistically significant long-term change is detected in either the mean or variability of western Russia July temperatures, implying that for this region an anthropogenic climate change signal has yet to emerge above the natural background variability.” They concluded their analysis “points to a primarily natural cause for the Russian heat wave,” noting the event “appears to be mainly due to internal atmospheric dynamical processes that produced and maintained an intense and long-lived blocking event.” There were no indications “blocking would increase in response to increasing greenhouse gases,” the authors reported.

In a study designed to assess the extent to which temperature variability may have increased in Austria since the late nineteenth century, Hiebl and Hofstätter (2012) took a systematic and objective approach to the issue of air temperature on a local scale, based on 140 years of data from Vienna-Hohe Warte, Kremsmunster, Innsbruck-University, Sonnblick, and Graz-University.

Starting from a low level of temperature variability around 1900, the two Austrian researchers reported a slow and steady rise in variability during

the twentieth century. They also reported a “period of persistently high variability levels before 1900,” which led them to conclude the “relatively high levels of temperature variability during the most recent warm decades from 1990 to 2010 are put into perspective by similar variability levels during the cold late 19th century.” They added, “when compared to its inter-annual fluctuations and the evolution of temperature itself, high-frequency temperature variability in the course of the recent 117–139 years appears to be a stable climate feature.” Hiebl and Hofstätter concluded concerns about “an increasing number and strength of temperature extremes in terms of deviations from the mean state in the past decades cannot be maintained” and “exaggerated statements seem irresponsible.”

Bohm (2012) observed “South Central Europe is among the spatially densest regions in terms of early instrumental climate data,” citing Auer *et al.* (2007). He explained this fact allows for successfully testing for homogeneity and developing “a larger number of very long instrumental climate time series at monthly resolution than elsewhere,” noting the resulting long time series subset of the greater alpine region provides a great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the “anthropogenic climate” of the past three decades. More specifically, he reported “the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year ‘normal periods’ from 1771–1800 to 1981–2010.”

Bohm found “the overwhelming majority of seasonal and annual sub-regional variability trends is not significant.” In the case of precipitation, for example, he observed, “there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period.” Regarding temperature, he reported “most of the variability trends are insignificantly decreasing.” In a “special analysis” of the recent 1981–2010 period that may be considered the first “normal period” under dominant greenhouse-gas-forcing, he found all extremes “remaining well within the range of the preceding ones under mainly natural forcing,” and “in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable.”

Bohm concludes “the ... evidence [is clear] that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that

the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period.”

Jeong *et al.* (2010) began by recognizing the model-based IPCC *Fourth Assessment Report* claim suggesting future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming, citing the work of Meehl and Tebaldi (2004) and Della-Marta *et al.* (2007). In a model-based assessment of this hypothesis, Jeong *et al.* investigated “the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO₂ concentration in a series of global climate model experiments,” where land surface processes are calculated by the Community Land Model (version 3) described by Oleson *et al.* (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables. The six scientists reported their calculations indicate “the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included,” and “examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature.” In addition, they found “the greening also tends to reduce the frequency and duration of heat waves.”

Jeong *et al.* indicated just how easily the incorporation of a new suite of knowledge, in even the best climate models of the day, can dramatically alter what the IPCC and others purport to be reality, including what they say about the frequency and duration of heat waves. Yet in conjunction with their model-based work, real-world data from the past revealed extreme temperatures tend to be less frequent and less severe during warmer climatic periods than during colder ones.

References

- Auer, I., Boehm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schoener, W., Ungersboeck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Mueller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., and Majstorovic, Z. 2007. HISTALP—Historical Instrumental climatological Surface Time series of the greater ALPine Region. *International Journal of Climatology* **27**: 17–46.
- Beniston, M. and Goyette, S. 2007. Changes in variability and persistence of climate in Switzerland: Exploring 20th century observations and 21st century simulations. *Global and Planetary Change* **57**: 1–15.
- Bohm, R. 2012. Changes of regional climate variability in central Europe during the past 250 years. *The European Physical Journal Plus* **127**: 10.1140/epjp/i2012-12054-6.
- Chase, T.N., Wolter, K., Pielke Sr., R.A., and Rasool, I. 2006. Was the 2003 European summer heat wave unusual in a global context? *Geophysical Research Letters* **33**: 10.1029/2006GL027470.
- Della-Marta, P.M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H. 2007. Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. *Climate Dynamics* **29**: 251–275.
- Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X.-W., Xu, T., and Murray, D. 2011. Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters* **38**: 10.1029/2010GL046582.
- Hiebl, J. and Hofstatter, M. 2012. No increase in multi-day temperature variability in Austria following climate warming. *Climatic Change* **113**: 733–750.
- IPCC. 2001 *Climate Change 2001. The Scientific Basis*. Cambridge University Press, Cambridge, UK.
- Jeong, S.-J., Ho, C.-H., Kim, K.-Y., Kim, J., Jeong, J.-H., and Park, T.-W. 2010. Potential impact of vegetation feedback on European heat waves in a 2 x CO₂ climate. *Climatic Change* **99**: 625–635.
- Jones, P.D. and Briffa, K.R. 2006. Unusual climate in northwest Europe during the period 1730 to 1745 based on instrumental and documentary data. *Climatic Change* **79**: 361–379.
- Katz, R.W. and Brown, B.G. 1992. Extreme events in a changing climate: variability is more important than averages. *Climatic Change* **21**: 289–302.
- Manrique, E. and Fernandez-Cancio, A. 2000. Extreme climatic events in dendroclimatic reconstructions from Spain. *Climatic Change* **44**: 123–138.
- Mearns, L.O., Giorgi, F., McDaniel, L., and Shields, C.

1995. Analysis of variability and diurnal range of daily temperature in a nested regional climate model: comparison with observations and doubled CO₂ results. *Climate Dynamics* **11**: 193–209.

Mearns, L.O., Schneider, S.H., Thompson, S.L., and McDaniel, L.R. 1990. Analysis of climate variability in general circulation models: comparison with observations and change in variability in 2 x CO₂ experiments. *Journal of Geophysical Research* **95**: 20,469–20,490.

Meehl, G.A. and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305**: 994–997.

Michaels, P.J., Balling Jr., R.C., Vose, R.S., and Knappenberger, P.C. 1998. Analysis of trends in the variability of daily and monthly historical temperature measurements. *Climate Research* **10**: 27–33.

Oleson, K.W., *et al.* 2004. *Technical Description of the Community Land Model (CLM)*. Technical Note NCAR/TN-461+STR.

Rebetez, M. 2001. Changes in daily and nightly day-to-day temperature variability during the twentieth century for two stations in Switzerland. *Theoretical and Applied Climatology* **69**: 13–21.

Schar, C., Vidale, P.L., Luthi, D., Frei, C., Haberil, C., Liniger, M.A., and Appenzeller, C. 2004. The role of increasing temperature variability in European summer heatwaves. *Nature* **427**: 332–336.

Stott, P.A., Stone, D.A., and Allen, M.R. 2006. Human contribution to the European heatwave of 2003. *Nature* **432**: 610–614.

Trigo, R.M., Garcia-Herrera, R., Diaz, J., Trigo, I.F., and Valente, M.A. 2005. How exceptional was the early August 2003 heatwave in France? *Geophysical Research Letters* **32**: 10.1029/2005GL022410.

7.1.3 North America

This subsection highlights several peer-reviewed studies from North America that do not support the IPCC-based claim that CO₂-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Shabbar and Bonsal (2003) examined trends and variability in the frequency, duration, and intensity of winter cold and warm spells in Canada during the second half of the twentieth century. For the period 1950–1998, they found western Canada experienced decreases in the frequency, duration, and intensity of winter cold spells. In the east, however, distinct increases in the frequency and duration of winter cold

spells occurred. With respect to winter warm spells, significant increases in both their frequency and duration were observed across most of Canada, with the exception of the extreme northeastern part of the country, where warm spells appear to be becoming shorter and less frequent. In the mean, therefore, there appear to be close-to-compensating trends in the frequency and intensity of winter cold spells in different parts of Canada, while winter warm spells appear to be increasing somewhat.

Khaliq *et al.* (2007) noted “extreme climate events are receiving increased attention because of the possibility of increases in their frequency and severity in future climate as a result of enhanced concentrations of greenhouse gases in the atmosphere and associated atmospheric warming” and “transient climate change simulations performed with both Global Climate Models and Regional Climate Models suggest increased frequencies of extreme high temperature events.” The five researchers assessed temporal changes in the frequency of occurrence and durations of heat waves based on data acquired at seven weather stations located in southern Quebec for the 60-year period 1941–2000. For heat spells defined in terms of daily maximum air temperature, the majority of extreme events showed “a negative time-trend with statistically significant decreases (at 10% level),” while almost all of the heat spells defined in terms of daily minimum air temperature showed “a positive time-trend with many strong increases (i.e., statistically significant at 5% level) at all of the stations.” Khaliq *et al.* stated “a possible interpretation of the observed trends is that the maximum temperature values are getting less hot and minimum temperature values are getting less cold with time,” signaling a reduction in overall temperature variability.

Bonsal *et al.* (2001) reported similar findings several years earlier, analyzing spatial and temporal characteristics of daily and extreme temperature-related variables across Canada over the period 1900–1998. They found “significant trends toward fewer days with extreme low temperature during winter, spring, and summer” as well as “trends toward more days with extreme high temperature in winter and spring,” but noted “these are not as pronounced as the decreases to extreme low values.” They found “no indication of any consistent changes to the magnitude of extreme high daily maximum temperature during summer” and “in general, day-to-day temperature variability has decreased over most of southern Canada during the twentieth century,” evidenced by a

greater increase in daily minimum (as opposed to maximum) extreme temperature values.

Taking a much longer view of the subject, Fallu *et al.* (2005) derived a 6,700-year temperature history for northern Quebec, Canada. They found after an initial increase in temperature that lasted from 6400 to 4900 cal. yr BP, a warm phase occurred from 4900 to ca. 1500 cal. yr BP. They reported the data obtained from this latter portion of the sediment core “suggest the most stable paleoclimatic conditions during this period.” Then came what they call the “recent cooling,” which lasted from ca. 1500 cal. yr BP to modern times, during which interval, they found, “lake water temperature apparently became increasingly unstable.” Accordingly, temperature variability in this region declined when the climate warmed.

Kunkel *et al.* (1999) investigated the occurrence of intense heat and cold waves from 876 locations in the southwestern United States over the period 1931–1997. They found a decline in exceedance probability threshold since 1930 for heat waves, and no trend was identified for cold spells (see Figures 7.1.3.1 and 7.1.3.2). As a result of these and other findings, Kunkel *et al.* concluded there has been “no evidence of changes in the frequency of intense heat or cold waves.”

Iskenderian and Rosen (2000) studied two mid-tropospheric temperature datasets spanning the past

40 years, calculating day-to-day variability within each month, season, and year. Averaged over the entire Northern Hemisphere, they found mid-tropospheric temperature variability exhibited a slight upward trend since the late 1950s in one of the datasets, but “this trend is significant in the spring season only.” They also admitted “the robustness of this springtime trend is in doubt” because the trend obtained from the other dataset was negative. For the conterminous United States, the two datasets showed “mostly small positive trends in most seasons” but none of these trends were statistically significant. Iskenderian and Rosen acknowledged they “cannot state with confidence that there has been a change in synoptic-scale temperature variance in the mid-troposphere over the United States since 1958.”

Two years later, in a study based on daily maximum (max), minimum (min), and mean air temperatures (T) from 1062 stations of the U.S. Historical Climatology Network, Robeson (2002) computed the slopes of the relationships defined by plots of daily air temperature standard deviation vs. daily mean air temperature for each month of the year for the period 1948–1997. This protocol revealed, in Robeson’s words, “for most of the contiguous USA, the slope of the relationship between the monthly mean and monthly standard deviation of daily Tmax and Tmin—the variance response—is either negative or near-zero.” This means, as he described it, “for

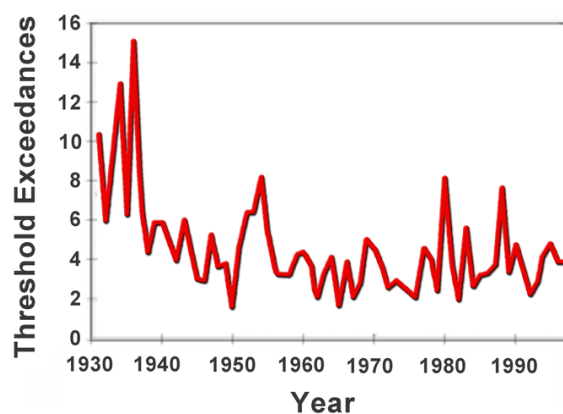


Figure 7.1.3.1. Heat wave exceedance threshold calculated as the number of days with a maximum temperature above the threshold for a 1.5% daily exceedance probability. The curve represents an average of 876 long-term stations in the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* 80: 1077–1098.

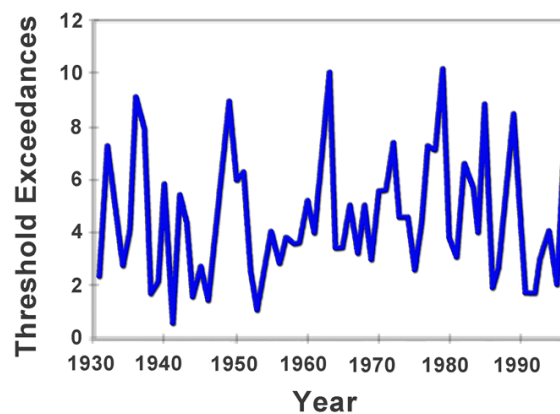


Figure 7.1.3.2. Cold wave exceedance threshold calculated as the number of days with a minimum temperature below the threshold for a 98.5% daily exceedance probability. The curve represents an average of 876 long-term stations from the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* 80: 1077–1098..

Observations: Extreme Weather

most of the contiguous USA, a warming climate should produce either reduced air-temperature variability or no change in air-temperature variability.” He also reported the negative relationships are “fairly strong, with typical reductions in standard deviation ranging from 0.2 to 0.5°C for every 1°C increase in mean temperature.”

DeGaetano and Allen (2002b) created a Daily Historical Climatology Network for Extreme Temperature (HCN-XT) dataset (DeGaetano and Allen, 2002a), which they used to determine how both hot and cold temperature extremes—defined in terms of the number of exceedances of the 90th, 95th, and 99th%iles of their respective databases—have varied across the contiguous United States over a number of different time scales.

Over the period 1960–1996, DeGaetano and Allen determined “a large majority of stations show increases in warm extreme temperature exceedances,” which would seem to corroborate model-based claims. They also reported “about 20% of the stations experience significant increases in warm maximum temperature occurrence,” again in seeming vindication of model-based claims. Furthermore, they noted “similar increases in the number of ≥ 2 and ≥ 3 runs of extreme temperatures occur across the country,” apparently substantiating claims of an increasing frequency of deadly heat waves.

However, when the two scientists extended their analyses further back in time, they obtained quite different results. Adding another 30 years of data onto the front ends of their databases, DeGaetano and Allen discovered there were “predominantly decreasing warm exceedance trends across the country during the 1930–96 period.” They found “in the 1930–96 period 70% of the stations exhibit decreasing high extreme maximum temperature trends.”

DeGaetano and Allen also found “trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th%ile across the United States are strongly influenced by urbanization.” With respect to daily warm minimum temperatures, for example, the slope of the regression line fit to the data of a plot of the annual number of 95th%ile exceedances vs. year over the period 1960–96 was found to be +0.09 exceedances per year for rural stations, +0.16 for suburban stations, and +0.26 for urban stations, making the rate of increase in extreme warm minimum temperatures at urban stations nearly three times greater than the increase at rural stations less affected by growing urban heat

islands. The rate of increase in the annual number of daily maximum temperature 95th%ile exceedances per year over the same time period was found to be 50% greater at urban stations than at rural stations. In spite of this vast uncorrected bias, when computed over the longer 1930–1996 period, 70% of all stations in the HCN-XT dataset exhibited “decreasing high extreme maximum temperature trends.”

DeGaetano and Allen’s findings clearly show extreme warm temperature events over the USA are no more prevalent currently than they were in the 1930s and may be even less prevalent now. Also, there is strong evidence implicating the growing influence of intensifying urban heat islands as being responsible for the apparent rapid increase in the mean annual temperatures for many locations over the last two decades of the twentieth century. Thus, even for the part of the world that may have experienced some net warming over the past 70 years, the warming is likely minimal.

Focusing on extreme temperatures experienced during heat waves, Redner and Petersen (2006) noted “almost every summer, there is a heat wave somewhere in the United States that garners popular media attention,” and it is only natural to wonder if global warming played a role in producing it. The two scientists set out to investigate “how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures,” after which they assessed the potential of global warming to produce such temperatures by comparing their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia.

The two researchers concluded “the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data.” They found they “cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures,” even with 126 years of real-world data. Such findings suggest it is not statistically justifiable to attribute any individual heat wave or “proliferation of record-breaking temperature events” to historical global warming, be it CO₂-induced or otherwise.

In an attempt to determine the role the planet’s mean temperature may have played in influencing temperature variability during the latter half of the twentieth century, Higgins *et al.* (2002) examined the influence of two important sources of Northern

Hemispheric climate variability—the El Niño/Southern Oscillation (ENSO) and the Arctic Oscillation—on winter (Jan–Mar) daily temperature extremes over the conterminous United States from 1950 to 1999. With respect to the Arctic Oscillation, there was basically no difference in the number of extreme temperature days between its positive and negative phases. With respect to the ENSO phenomenon, however, Higgins *et al.* found during El Niño years, the total number of extreme temperature days decreased by approximately 10%, while during La Niña years they increased by approximately 5%. With respect to winter temperatures throughout the conterminous United States, therefore, the model-based contention that warmer global temperatures—such as are typically experienced during El Niño years—will produce more extreme weather conditions is unsupported, as Higgins *et al.* found the opposite to be true.

Contrary to model projections, the research reported here concludes a warmer climate does not tend to produce a more variable climate. The data suggest a warmer climate may be less variable and less extreme, if any change occurs at all. The scientific literature does not support projections of more frequent and intense summer heat waves.

References

- Bonsal, B.R., Zhang, X., Vincent, L.A., and Hogg, W.D. 2001. Characteristics of daily and extreme temperatures over Canada. *Journal of Climate* **14**: 1959–1976.
- DeGaetano, A.T. and Allen, R.J. 2002a. A homogenized historical temperature extreme dataset for the United States. *Journal of Atmospheric and Oceanic Technology* **19**: 1267–1284.
- DeGaetano, A.T. and Allen, R.J. 2002b. Trends in twentieth-century temperature extremes across the United States. *Journal of Climate* **15**: 3188–3205.
- Fallu, M.-A., Pienitz, R., Walker, I.R., and Lavoie, M. 2005. Paleolimnology of a shrub-tundra lake and response of aquatic and terrestrial indicators to climatic change in arctic Quebec, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* **215**: 183–203.
- Higgins, R.W., Leetmaa, A., and Kousky, V.E. 2002. Relationships between climate variability and winter temperature extremes in the United States. *Journal of Climate* **15**: 1555–1572.
- Iskenderian, H. and Rosen, R.D. 2000. Low-frequency signals in midtropospheric submonthly temperature variance. *Journal of Climate* **13**: 2323–2333.
- Khalik, M.N., Gachon, P., St-Hilaire, A., Quarda, T.B.M.J., and Bobee, B. 2007. Southern Quebec (Canada) summer-season heat spells over the 1941–2000 period: an assessment of observed changes. *Theoretical and Applied Climatology* **88**: 83–101.
- Khandekar, L. 2003. Comment on WMO statement on extreme weather events. *EOS, Transactions, American Geophysical Union* **84**: 428.
- Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098.
- Redner, S. and Petersen, M.R. 2006. Role of global warming on the statistics of record-breaking temperatures. *Physical Review E* **74**: 061114.
- Robeson, S.M. 2002. Relationships between mean and standard deviation of air temperature: implications for global warming. *Climate Research* **22**: 205–213.
- Shabbar, A. and Bonsal, B. 2003. An assessment of changes in winter cold and warm spells over Canada. *Natural Hazards* **29**: 173–188.

7.1.4 Other Areas

This subsection highlights several peer-reviewed studies from various other regions of the globe (outside of Asia, Europe, and North America, examined in the preceding subsections) that do not support the IPCC-based claim that CO₂-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Starting with a long temporal view of the subject, Oppo *et al.* (1998) studied sediments from Ocean Drilling Project site 980 on the Feni Drift (55.5°N, 14.7°W) in the North Atlantic. Working with a core formed 500,000 to 340,000 years ago, they analyzed $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ obtained from benthic foraminifera and $\delta^{18}\text{O}$ obtained from planktonic foraminifera to develop histories of deep water circulation and sea surface temperature (SST), respectively. They discovered a number of persistent climatic oscillations with periods of 6,000, 2,600, 1,800, and 1,400 years that traversed the entire length of the sediment core record, extending through glacial and interglacial epochs alike. These SST variations, which were found to be in phase with deep-ocean circulation changes, were on the order of 3°C during cold glacial maxima but only 0.5 to 1°C during warm interglacials.

McManus *et al.* (1999), who also examined a

half-million-year-old deep-sea sediment core from the eastern North Atlantic, reported similar findings. The authors noted significant SST oscillations throughout the record, and they too were of much greater amplitude during glacial periods (4 to 6°C) than during interglacials (1 to 2°C). Likewise, in another study of a half-million-year-long sediment core from the same region, Helmke *et al.* (2002) found the most stable of all climates held sway during what they called “peak interglaciations” or periods of greatest warmth. The temperatures in each of the interglacials that preceded our current interglacial were warmer than the present one, and by an average temperature in excess of 2°C, as determined by Petit *et al.* (1999). Thus, even if Earth were to continue its recent recovery from the global chill of the Little Ice Age, that warming likely would cause a decrease in temperature variability, as evidenced by real-world data pertaining to the past half-million years.

Shifting the temporal focus to that of the past millennium, Cook *et al.* (2002) reported the results of a tree-ring study of long-lived silver pines on the West Coast of New Zealand’s South Island. The chronology they derived provided a reliable history of Austral summer temperatures from AD 1200 to 1957, after which measured temperatures were used to extend the history to 1999. Cook *et al.* stated their reconstruction showed “there have been several periods of above and below average temperature that have not been experienced in the 20th century,” indicating New Zealand climate was much less variable over the last century than it was over the prior 700 years.

Focusing on a finer temporal resolution, Ault *et al.* (2009) employed 23 coral $\delta^{18}\text{O}$ records from the Indian and Pacific Oceans to extend the observational record of decadal climate variability in the region to AD 1850–1990, noting “coral records closely track tropical Indo-Pacific variability on interannual to decadal timescales (Urban *et al.*, 2000; Cobb *et al.*, 2001; Linsley *et al.*, 2008).” The seven scientists identified “a strong decadal component of climate variability” that “closely matches instrumental results from the 20th century.” In addition, they noted the decadal variance was much greater between 1850 and 1920 than it was between 1920 and 1990. The researchers “infer that this decadal signal represents a fundamental timescale of ENSO variability” whose enhanced variance in the early half of the record “remains to be explained.”

In a study designed to investigate the IPCC contention “that in the future the frequency of

extreme temperature events and their magnitude will increase,” Rusticucci and Barrucand (2004) investigated how such a claim might apply to Argentina, deriving trends of the mean, the standard deviation, and the extreme maximum and minimum daily temperatures over the period 1959–1998 based on “a deeply quality-controlled stations database.” According to the two Argentine scientists, “the variable that presents the largest number of stations with observed significant trends is the minimum temperature in summer, where positive trend values were found at many stations over 4°C (100 yr)⁻¹.” They also reported “the maximum temperature in summer presented strong negative values of the same magnitude in stations located in central Argentina.” The researchers concluded “a large fraction of the area that yields most of the agricultural production of Argentina should result in reduced air temperature variability in the case of a warming climate, as is also shown by Robeson (2002) for the United States.”

Rusticucci (2012) further examined the claim global warming will increase climatic variability, reviewing many studies that have explored this subject throughout the length and breadth of South America, particularly as it applies to daily maximum and minimum air temperatures. The Buenos Aires researcher found the most significant trends exist in the evolution of the daily minimum air temperature, with “positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature),” as well as negative trends in the cold extremes of the minimum temperature. She states this was the case “in almost all studies.” By contrast, she writes, “on the maximum temperature behavior there is little agreement, but generally the maximum temperature in South America has decreased.”

In general, over most of South America there has been a decrease in the extremeness of both daily maximum and minimum air temperatures, with the maximums declining and the minimums rising. These findings are beneficial, as Rusticucci notes cold waves and frost are especially harmful to agriculture, one of the main economic activities in South America. Cold waves and frost days were on the decline nearly everywhere throughout the continent during the warming of the twentieth century.

Alexander *et al.* (2006) developed what they call “the most up-to-date and comprehensive global picture of trends in extreme temperature.” They analyzed results from a number of workshops held in data-sparse regions and high-quality station data

supplied by numerous scientists from around the world, after which several seasonal and annual temperature indices for the period 1951–2003 were calculated and gridded, and trends in the gridded fields were computed and tested for statistical significance.

Alexander *et al.* report “over 70% of the land area sampled showed a significant increase in the annual occurrence of warm nights while the occurrence of cold nights showed a similar proportion of significant decrease,” with some regions experiencing “a more than doubling of these indices.” At the other end of the scale, they found only 20% of the land area sampled exhibited statistically significant changes, specifically noting “maximum temperature extremes have also increased but to a lesser degree.” These findings, in the words of the researchers, “agree with earlier global studies (e.g., Jones *et al.*, 1999) and regional studies (e.g., Klein Tank and Konnen, 2003; Manton *et al.*, 2001; Vincent and Mekis, 2006; Yan *et al.*, 2002), which imply that rather than viewing the world as getting hotter it might be more accurate to view it as getting less cold.”

References

- Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., and Vazquez-Aguirre, J.L. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* **111**: 10.1029/2005JD006290.
- Ault, T.R., Cole, J.E., Evans, M.N., Barnett, H., Abram, N.J., Tudhope, A.W., and Linsley, B.K. 2009. Intensified decadal variability in tropical climate during the late 19th century. *Geophysical Research Letters* **36**: 10.1029/2008GL036924.
- Cobb, K.M., Charles, C.D., and Hunter, D.E. 2001. A central tropical Pacific coral demonstrates Pacific, Indian, and Atlantic decadal climate connections. *Geophysical Research Letters* **28**: 2209–2212.
- Cook, E.R., Palmer, J.G., Cook, B.I., Hogg, A., and D’Arrigo, R.D. 2002. A multi-millennial palaeoclimatic resource from *Lagarostrobos colensoi* tree-rings at Oroko Swamp, New Zealand. *Global and Planetary Change* **33**: 209–220.
- Helmke, J.P., Schulz, M., and Bauch, H.A. 2002. Sediment-color record from the northeast Atlantic reveals patterns of millennial-scale climate variability during the past 500,000 years. *Quaternary Research* **57**: 49–57.
- Klein Tank, A.M.G. and Konnen, G.P. 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. *Journal of Climate* **16**: 3665–3680.
- Linsley, B.K., Zhang, P., Kaplan, A., Howe, S.S., and Wellington, G.M. 2008. Interdecadal-decadal climate variability from multicoral oxygen isotope records in the South Pacific Convergence Zone region since 1650 A.D. *Paleoceanography* **23**: 10.1029/2007PA001539.
- Manton, M.J., Della-Marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I., and Yee, D. 2001. Trends in extreme daily rainfall and temperature in southeast Asia and the South Pacific: 1916–1998. *International Journal of Climatology* **21**: 269–284.
- McManus, J.F., Oppo, D.W., and Cullen, J.L. 1999. A 0.5-million-year record of millennial-scale climate variability in the North Atlantic. *Science* **283**: 971–974.
- Oppo, D.W., McManus, J.F., and Cullen, J.L. 1998. Abrupt climate events 500,000 to 340,000 years ago: Evidence from subpolar North Atlantic sediments. *Science* **279**: 1335–1338.
- Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.
- Robeson, S. 2002. Relationships between mean and standard deviation of air temperature: Implications for global warming. *Climate Research* **22**: 205–213.
- Rusticucci, M. 2012. Observed and simulated variability of extreme temperature events over South America. *Atmospheric Research* **106**: 1–17.
- Rusticucci, M. and Barrucand, M. 2004. Observed trends and changes in temperature extremes over Argentina. *Journal of Climate* **17**: 4099–4107.
- Urban, F.E., Cole, J.E., and Overpeck, J.T. 2000. Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. *Nature* **407**: 989–993.
- Vincent, L.A. and Mekis, E. 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the 20th century. *Atmosphere and Ocean* **44**: 177–193.
- Yan, Z., Jones, P.D., Davies, T.D., Moberg, A., Bergstrom,

H., Camuffo, D., Cocheo, C., Maugeri, M., Demaree, G.R., Verhoeve, T., Thoen, E., Barriendos, M., Rodriguez, R., Martin-Vide, J., and Yang, C. 2002. Trends of extreme temperatures in Europe and China based on daily observations. *Climatic Change* **53**: 355–392.

7.1.5 Cold Weather Extremes

The global mean temperature trend, estimated by the UK Met Office, shows a lack of warming of Earth's climate during the past 16 years. In addition, there is mounting evidence of a recent increase in cold weather extremes in many parts of the world.

The brunt of recent cold weather extremes seems to have been borne by Europe, which has experienced extremely cold winters for the past six years. The latest round of cold European weather (in 2013) brought large amounts of snow in northern France, Germany, Belgium, and Poland. Berlin is reported to have experienced its coldest winter in 100 years. Also, Hungary and Poland reported excessive snow and bitterly cold weather in the month of March. Just last year (February 2012) most of eastern and Central Europe, including Belarus, Poland, Slovakia, and the Czech Republic, experienced severe cold weather, with low temperatures at some locales reaching -40°C and below. The cold weather caused several hundred deaths during February 2012 in the Czech Republic, Hungary, and Poland.

The winters of 2009–2010 and 2010–2011 were equally cold and snowy in parts of Europe and North America (Seager *et al.*, 2010; Taws *et al.*, 2011). In South America, winters have become colder during the past six years. In July 2007, parts of Argentina reported low temperatures at -25°C, and snow fell in Buenos Aires in July 2007 – the city's first snowfall since 1918. July 2013 was significantly colder in the southern regions of South America, with snow reported in more than 75 locales in Argentina and southern Brazil during the week of July 20–25, 2013.

In tropical Asia, winters also have become colder in the past ten years. The severity of the cold winter of 2002–2003 was felt as far south as Vietnam and Bangladesh, where several hundred people died of exposure. Also, winters in Northern India have become colder in the past six years or so. The past winter (December 2012–January 2013) brought several low temperature records (0°C to -5°C) in parts of NW India and in many large cities such as New Delhi, which endured its coldest January in 40 years. Several hundred people died from exposure to the cold weather there as well, as houses in North India

are not equipped with heating or good insulation.

The media rarely mention such extreme cold weather events, and the past few years have brought relatively few studies on cold winters. Most such publications have been by European meteorologists and climate scientists. Among the papers reported in recent literature are those by Benestad (2010), Cattiaux *et al.* (2010), Haigh (2010), Lockwood *et al.* (2011), Petoukhov and Semenov (2010), Sirocko *et al.* (2012), Wang *et al.* (2010), and Woollings *et al.* (2010). Many of these papers suggest reduced solar activity played a prominent role in the observed colder winters.

Some solar scientists are investigating the possibility of the Sun entering into a Grand Solar Minimum (GSM), which could manifest itself within two decades (Lockwood *et al.*, 2011). How an approaching GSM might impact Earth's climate is being studied extensively. Papers by Schindell *et al.*, (2001) and others discussed the impact of past low solar activity on regional and global climate. During the last GSM, known popularly as the Maunder Minimum, Earth's climate underwent what has come to be known in climatic terms as the Little Ice Age (LIA), a period that brought the coldest temperatures of the Holocene, or current interglacial, in which we live. Lasting about 200 years (approximately 1650–1850), the brunt of the LIA was felt in Europe, which experienced long and extreme winters and cooler summers. Soon and Yaskell (2003) provide a comprehensive discussion of the climatic impact of the Maunder Minimum. Whether the Sun is indeed approaching a new Grand Solar Minimum, however, remains to be seen.

Along with a recent spate of cold temperature extremes experienced across the globe, record snowfall has occurred in many places, especially in the Northern Hemisphere. The winter of December 2012–March 2013 brought several large snowstorms across Europe and North America. The first two weeks of March saw several heavy to very heavy snowfalls in Northern France, Germany, and Belgium, with snowfall amounts reaching 25cm and more in many places. Over North America, the winter of 2012–2013 was long and snowy from the southwestern U.S. to the upper Midwest. A February 26–27 snowstorm dumped more than 45cm of snow on Amarillo, Texas. The same storm dumped more than 30 cm of snow on parts of central Ontario and Toronto as it moved in a SW-NE track. In early to mid-March, snowfalls varying from 20cm to 30cm fell in several states from Colorado to Minnesota. On

the Canadian Prairies, the week of March 17–24 saw heavy snowfalls (15–25cm) in parts of Alberta and Saskatchewan.

Other examples of recent heavy snowfall include:

Winter 2011–2012:

Alaska. Some of the heaviest snowfalls ever recorded fell in January 2012. The fishing community of Cordova (east side of Prince William Sound) received close to 450cm of snow between November 2011 and January 2012. At Valdez, more than 350cm of snow fell in the first two weeks of January.

Canadian Rockies. The Canadian Rockies experienced some of the region's heaviest-ever recorded snowfalls in many areas. Sunshine Village (a popular ski resort on the Alberta/British Columbia border) set an all-time record with more than 915cm of snow by March 25. At Mount Norquay (near Banff, Alberta) more than 900cm of snow fell from November to March. At Ferni Alpine Resort (British Columbia) more than 1,000cm of snow fell during the 2011–2012 winter season, a record.

Europe. One of the most severe winters in Eastern Europe brought snowfalls of 25cm and more. In the eastern Adriatic Sea, more than 35cm of snow fell near Montenegro on February 10–11.

Japan. Snowfall several tens of cm deep fell in parts of Japan during February 12–14, 2012.

Winter 2010–2011: More than 80cm of snow fell in a two-day period (5–6 December 2010) in London, Ontario (Canada). Montreal received more than 30cm (December 6–7).

Winter 2009–2010: The largest snow cover extent in the history of the contiguous United States occurred in December 2009. The mid-Atlantic cities of Baltimore, Philadelphia, and Washington, DC had their snowiest winters ever (each received more than 150cm of snow). The winter of 2009–2010 was the snowiest since 1977–78 in the Northern Hemisphere. Khandekar (2010) reported additional snowfall and cold weather records during the previous 10 years.

The latest snow cover data archived at the Rutgers Northern Hemisphere snow data center (US) are shown in Table 7.1.5.1. The winter of 2012–2013 was the fourth snowiest in Northern Hemisphere history. Five winter seasons (December–February) since 2000 are among the top six winters for snow accumulation. If the November snow data were included in the table, this past winter would be the second snowiest winter during the past 40 years.

Winter snow accumulation in the Northern

Hemisphere has been increasing in recent years. Such observations run counter to model projections suggesting there should be less snowfall occurring in response to CO₂-induced global warming.

References

Benestad, R.E. 2010. Low solar activity is blamed for winter chill over Europe. *Environmental Research Letters* **5**: 021001 doi:10.1088/1748-9326/5/2/021001.

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., and Codron, F. 2010. Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters* **37**: L20704, doi:10.1029/2010GL044613.

Haigh, J.D. 2003. The effects of solar variability on the Earth's climate. *Philosophical Transactions of the Royal Society of London A* **361**: 95–111.

Khandekar, M.L. 2010. Weather extremes of summer 2010; Global warming or natural variability? *Energy & Environment* **21**: 1005–1010.

Lockwood, M., Harrison, R.G., Woollings, T., and Solanki, S.K. 2010. Are cold winters in Europe associated with low solar activity? *Environmental Research Letters* **5**: 024001 doi:10.1088/1748-9326/5/2/024001.

Lockwood, M., Owens, M.J., Barnard, L., Davis, C.J., and Steinhilber, F. 2011. The persistence of solar activity indicators and the descent of the Sun into Maunder Minimum conditions. *Geophysical Research Letters* **38**: L22105, doi:10.1029/2011GL049811.

Seager, R., Kushnir, Y., Nakamura, J., Ting, M., and Naik, N. 2010. Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophysical research Letters* **37**: L14703, doi:10.1029/2010GL043830.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., and Waple, A. 2001. Solar forcing of regional climate change during the Maunder Minimum. *Science* **294**: 2149–2152.

Sirocko, F., Brunck, H., and Pfahl, S. 2012. Solar influence on winter severity in central Europe. *Geophysical Research Letters* **39**: L16704, doi:10.1029/2012GL052412.

Soon, W. and Yaskell, S.H. 2003. *The Maunder Minimum and the Variable Sun-Earth Connection*. World Scientific Publishing.

Taws, S.L., Marsh, R., Wells, N.C., and Hirschi, J. 2011. Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. *Geophysical Research Letters* **38**: L20601, doi:10.1029/2011GL048978.

Wang, C., Liu, H., and Lee, S.-K. 2010. The record

Table 7.1.5.1. The top 15 winter season snowfall accumulation totals in the Northern Hemisphere.

Season (Dec–Feb)	Snow Accumulation (Millions km ²)
1977–78	48.403
2009–10	47.507
2010–11	47.183
2012–13	47.150
2007–08	46.910
2002–03	46.830
1978–79	46.730
1984–85	46.722
1985–86	46.577
1971–72	46.517
1970–71	46.317
1968–69	46.297
1966–67	46.073
1981–82	45.810
2011–12	45.803

breaking cold temperatures during the winter of 2009/10 in the Northern Hemisphere. *Atmospheric Science Letters* **11**: 161–168.

Woollings, T., Lockwood, M., Masato, G., Bell, C., and Gray, L. 2010. Enhanced signature of solar variability in Eurasian winter climate. *Geophysical Research Letters* **37**: L20805, doi:10.1029/2010GL044601.

7.2 Heat Waves

In response to an increase in mean global air temperature, the IPCC contends there will be more frequent and severe extremes of various weather phenomena, including more frequent and extreme heat waves. In its *Fifth Assessment Report*, the IPCC states “models also project increases in the duration, intensity and spatial extent of heat-waves and warm spells for the near term” (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). Furthermore, they suggest an anthropogenic influence is already underway, stating “we now conclude that it is likely that human influence has significantly increased the probability of some observed heat waves” (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). Although much of the material in the preceding section of this chapter (Section 7.1, Temperature) reveals the IPCC claims on heat waves have little support in the scientific literature, this section examines additional studies that also explain why the IPCC projections are likely wrong.

Deng *et al.* (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 to examine trends in heat waves in the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. The three Chinese researchers report their study area experienced a mean annual warming trend with slight decreasing trends in spring and summer temperatures. They also found extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that “the frequencies of heat waves and long heat waves in the recent years were no larger than the late 1950s and early 1960s.” They observed, “coupled with the extreme low frequency in the 1980s, heat waves and long heat waves showed a slight linear decreasing trend in the past 50 years.” They noted the most recent frequency of heat waves “does not outnumber 1959 or 1961” and “none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003.”

Deng *et al.* concluded, citing Tan *et al.* (2007), “compared with the 1950s and 1960s, short heat waves instead of long heat waves have taken place more often,” which, as they describe it, “is desirable, as longer duration leads to higher mortality.”

Redner and Petersen (2006) investigated “how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures.” They compared their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia. The results of their mathematical analysis led them to conclude “the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data.” They also stated they “cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures,” even with 126 years of data.

Fischer *et al.* (2007) and Robock *et al.* (2000) may provide some insight into why the models are failing in their heat wave projections.

Fischer *et al.* conducted regional climate simulations, both with and without land-atmosphere coupling, for the major European summer heat waves of 1976, 1994, 2003, and 2005. The authors found

during all simulated heat wave events, “soil moisture-temperature interactions increase the heat wave duration and account for typically 50–80% of the number of hot summer days,” noting “the largest impact is found for daily maximum temperatures,” which were amplified by as much as 2–3°C in response to observed soil moisture deficits in their study.

Robock *et al.* developed a massive collection of soil moisture data from more than 600 stations spread across a variety of climatic regimes (including the former Soviet Union, China, Mongolia, India, and the United States). They found “for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen.” This counterintuitive finding was confirmed by Robock *et al.* (2005) and Li *et al.* (2007), the latter noting when exposed to elevated concentrations of atmospheric CO₂, “many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere,” so “more water is likely to be stored in the soil or [diverted to] runoff.” Gedney *et al.* (2006) confirmed the latter phenomenon. Pearce (2006) quoted Gedney saying “climate change on its own would have slightly reduced runoff, whereas the carbon dioxide effect on plants would have increased global runoff by about 5%,” with the combined effect of the two competing phenomena leading to the 3–4% flow increase actually observed.

In light of the complementary global soil moisture and river runoff observations, it would appear, in general, the anti-transpiration effect of the historical rise in the air’s CO₂ content has more than compensated for the soil-drying effect of global warming. Fischer *et al.* (2007) found soil moisture depletion greatly augments both the intensity and duration of summer heat waves, while Robock *et al.* (2000, 2005) and Li *et al.* (2007) found global soil moisture has increased over the past half-century, likely as a result of the anti-transpiration effect of atmospheric CO₂ enrichment—as Gedney *et al.* (2006) also have found to be the case with closely associated river runoff. Thus the increase in soil moisture caused by rising atmospheric CO₂ concentrations will tend to decrease both the intensity and duration of summer heat waves as time progresses. That relationship may explain why historic heat waves in locations such as Philadelphia and the Three Gorges area of China have not increased in response to what the IPCC often refers to as the unprecedented warming of the late twentieth and early twenty-first centuries.

Jeong *et al.* (2010) observe modeling studies in the IPCC’s *Fourth Assessment Report* (AR4) suggest future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming. Jeong *et al.* investigated “the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO₂ concentration in a series of global climate model experiments,” where land surface processes were calculated by the Community Land Model (version 3) described by Oleson *et al.* (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables.

Their calculations revealed “the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included,” and “examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature.” The scientists found “the greening also tends to reduce the frequency and duration of heat waves.”

References

- Della-Marta, P.M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H. 2007. Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability. *Climate Dynamics* **29**: 251–275.
- Deng, H., Zhao, F., and Zhao, X. 2012. Changes of extreme temperature events in Three Gorges area, China. *Environmental and Earth Sciences* **66**: 1783–1790.
- Fischer, E.M., Seneviratne, S.I., Luthi, D., and Schar, C. 2007. Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters* **34**: 10.1029/2006GL029068.
- Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**: 835–838.
- Jeong, S.-J., Ho, C.-H., Kim, K.-Y., Kim, J., Jeong, J.-H., and Park, T.-W. 2010. Potential impact of vegetation

feedback on European heat waves in a 2 x CO₂ climate. *Climatic Change* **99**: 625–635.

Li, H., Robock, A., and Wild, M. 2007. Evaluation of Intergovernmental Panel on Climate Change Fourth Assessment soil moisture simulations for the second half of the twentieth century. *Journal of Geophysical Research* **112**: 10.1029/2006JD007455.

Meehl, G.A. and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* **305**: 994–997.

Oleson, K.W., *et al.* 2004. *Technical Description of the Community Land Model (CLM)*. Technical Note NCAR/TN-461+STR.

Pearce, F. 2006. Increased CO₂ may cause plant life to raise rivers. *NewScientist.com*. www.newscientist.com/article/dn8727-increased-co2-may-cause-plant-life-to-raise-rivers.html.

Redner, S. and Petersen, M.R. 2006. Role of global warming on the statistics of record-breaking temperatures. *Physical Review E* **74**: 061114.

Robock, A., Mu, M., Vinnikov, K., Trofimova, I.V., and Adamenko, T.I. 2005. Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet). *Geophysical Research Letters* **32**: 10.1029/2004GL021914.

Robock, A., Vinnikov, K.Y., Srinivasan, G., Entin, J.K., Hollinger, S.E., Speranskaya, N.A., Liu, S., and Namkhai, A. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* **81**: 1281–1299.

Tan, J., Zheng, Y., Song, G., Kalkstein, L.S., Kalkstein, A.J., and Tang, Z.X. 2007. Heat wave impacts on mortality in Shanghai, 1998 and 2003. *International Journal of Biometeorology* **51**: 193–200.

7.3 Fire

According to model-based predictions, larger and more intense wildfires will become more frequent as a result of CO₂-induced global warming. Many scientists have begun to search for a link between fire and climate, often examining past trends to see if they support the models' projections. The following section examines what has been learned in this regard, beginning with a review of studies conducted in North America and ending with a discussion of the planet as a whole.

Campbell and Campbell (2000) analyzed pollen and charcoal records obtained from sediment cores retrieved from three small ponds—South Pond (AD 1655–1993), Birch Island Pond (AD 1499–1993), and Pen 5 Pond (400 BC–AD 1993)—in Canada's Elk

Island National Park, which covers close to 200 km² of the Beaver Hills region of east-central Alberta. “Counter to the intuitive increase in fire activity with warmer and drier climate,” the Canadian researchers reported, “declining groundwater levels during the Medieval Warm Period [MWP] allowed the replacement of substantial areas of shrub birch with the less fire-prone aspen, causing a decline in fire frequency and/or severity, while increasing carbon storage on the landscape,” as implied by their Pen 5 Pond data. They concluded this scenario “is likely playing out again today,” as all three of the sites they studied “show historic increases in *Populus* pollen and declines in charcoal.”

Carcaillet *et al.* (2001) developed high-resolution charcoal records from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada. The scientists determined whether vegetation change or climate change was the primary determinant of changes in fire frequency, comparing their fire history with hydroclimatic reconstructions derived from $\delta^{18}\text{O}$ and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago, when it was significantly warmer than it is today, they reported “fire intervals were double those in the last 2,000 years,” meaning fires were only half as frequent throughout the earlier, warmer period as they were during the subsequent, cooler period. They also determined “vegetation does not control the long-term fire regime in the boreal forest,” but instead, “climate appears to be the main process triggering fire.” In addition, they report “dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al.*, 1990; Larsen, 1997; Weir *et al.*, 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al.*, 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993).” The scientists concluded a “future warmer climate is likely to be less favorable for fire ignition and spread in the east Canadian boreal forest than over the last 2 millennia.”

Le Goff *et al.* (2007) investigated “regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years vs. non-fire years in the Waswanipi area of northeastern Canada [49.5–50.5°N, 75–76.5°W], and the long-term relationship with large-scale climate variations ...

using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps.” Their analysis showed instead of the interval of time between wildfires shortening as time progressed and the climate warmed, there was “a major lengthening of the fire cycle,” which expanded “from 99 years before 1940 to 282 years after 1940.” In addition, Le Goff *et al.* noted “in the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 [or the “end of the Little Ice Age,” as they describe it] (Bergeron and Archambault, 1993; Larsen, 1996) and a further decrease after 1940 (Bergeron *et al.*, 2001, 2004a,b, 2006).”

Similar findings were reported by Lauzon *et al.* (2007) while investigating the fire history of a 6,480-km² area located in the Baie-Des-Chaleurs region of Gaspésie at the southeastern edge of Quebec “using Quebec Ministry of Natural Resource archival data and aerial photographs combined with dendro-chronological data.” Coincident with the 150-year warming that led to the demise of the Little Ice Age and the establishment of the Current Warm Period, the three researchers reported there was “an increase in the fire cycle from the pre-1850 period (89 years) to the post-1850 period (176 years),” and “both maximum and mean values of the Fire Weather Index decreased statistically between 1920 and 2003.” During the latter period, they observed, “extreme values dropped from the very high to high categories, while mean values changed from moderate to low categories.” In contrast with model projections, and in this particular part of the world, twentieth century global warming has led to a significant decrease in the frequency of forest fires, as weather conditions conducive to their occurrence have become less prevalent and extreme.

Girardin *et al.* (2006) hypothesized “human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures.” They noted “climate change therefore could cause longer fire seasons (Wotton and Flannigan, 1993), with greater fire activity and greater incidence of extreme fire activity years (Colombo *et al.*, 1998; Parker *et al.*, 2000).” To provide a more rigorous test of the hypothesis than could be provided by the historical observational record, they determined it should be placed in a much longer context. Girardin

et al. inferred past area burned in Ontario for the period AD 1781–1982 by regressing tree-ring chronologies against actual area burned data and developing transfer functions they used “to estimate annual area burned at times during which there were no instrumental data.”

The three researchers reported “while in recent decades area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s.” The researchers further noted “the most recent increase in area burned in the province of Ontario was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s–1960s),” despite the fact “humans during the past decades have been an important source of fire ignition.” Consequently, although according to theory “one should expect greater area burned in a changing climate,” their findings revealed just the opposite.

The robust nature of the Canadian scientists’ findings is substantiated by “numerous studies of forest stand age distributions [an independent way of assessing the matter] across the Canadian boreal forest [a larger area than Ontario alone] [that] report lower fire activity since circa 1850 (Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Bergeron *et al.*, 2001, 2004a, 2004b; Tardif, 2004).”

Beatty and Taylor (2009) developed a 14,000-year record of fire frequency based on high-resolution charcoal analysis of a 5.5-m-long sediment core extracted from Lily Pond (39°3'26"N, 120°7'21"W) in the General Creek Watershed on the west shore of Lake Tahoe in the northern Sierra Nevada in California (USA), as well as a 20-cm-long surface core that “preserved the sediment-water interface.”

They found “fire episode frequency was low during the Lateglacial period but increased through the middle Holocene to a maximum frequency around 6500 cal. yr BP,” which “corresponded with the Holocene temperature maximum (7000–4000 cal. yr BP).” Thereafter, as the temperature gradually declined, so too did fire frequency, except for a multicentury aberration they described as “a similar peak in fire episode frequency [that] occurred between c. 1000 and 600 cal. yr BP during the ‘Medieval Warm Period,’” which they indicated was followed by an interval “between c. 500 and 200 cal. yr BP with few charcoal peaks [that] corresponded with the so-called ‘Little Ice Age.’” Arriving at the present, they find the “current fire episode frequency on the west shore of Lake Tahoe is at one of its lowest points in at least the last 14,000 years.”

Observations: Extreme Weather

A contrary example, where warming does appear to have enhanced fire occurrence, is provided by Pierce *et al.* (2004), who dated fire-related sediment deposits in alluvial fans in central Idaho, USA, in a research program designed to reconstruct Holocene fire history in xeric ponderosa pine forests and to look for links to past climate change. This endeavor focused on tributary alluvial fans of the South Fork Payette (SFP) River area, where fans receive sediment from small but steep basins in weathered batholith granitic rocks conducive to post-fire erosion. Altogether, they obtained 133 AMS ^{14}C -derived dates from 33 stratigraphic sites in 32 alluvial fans. In addition, they compared their findings with those of Meyer *et al.* (1995), who had earlier reconstructed a similar fire history for nearby Yellowstone National Park in Wyoming, USA.

Pierce *et al.*'s work revealed "intervals of stand-replacing fires and large debris-flow events are largely coincident in SFP ponderosa pine forests and Yellowstone, most notably during the 'Medieval Climatic Anomaly' (MCA), ~1,050-650 cal. yr BP." They also noted "in the western USA, the MCA included widespread, severe multidecadal droughts (Stine, 1998; Woodhouse and Overpeck, 1998), with increased fire activity across diverse northwestern conifer forests (Meyer *et al.*, 1995; Rollins *et al.*, 2002)."

Following the Medieval Warm Period and its frequent large-event fires was the Little Ice Age, when, as Pierce *et al.* described it, "colder conditions maintained high canopy moisture, inhibiting stand-replacing fires in both Yellowstone lodgepole pine forests and SFP ponderosa pine forests (Meyer *et al.*, 1995; Rollins *et al.*, 2002; Whitlock *et al.*, 2003)." Subsequently, they reported, "over the twentieth century, fire size and severity have increased in most ponderosa pine forests," which they suggest may be largely due to "the rapidity and magnitude of twentieth-century global climate change."

Westerling *et al.* (2006), who compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydroclimatic and land-surface data, reached similar conclusions. Their findings are succinctly summarized by Running (2006) in an accompanying Perspective, where he wrote "since 1986, longer warmer summers have resulted in a fourfold increase of major wildfires and a sixfold increase in the area of forest burned, compared to the period from 1970 to 1986," noting also "the length of the active wildfire season in the western United States has increased by

78 days, and that the average burn duration of large fires has increased from 7.5 to 37.1 days." In addition, he states, "four critical factors—earlier snowmelt [by one to four weeks], higher summer temperatures [by about 0.9°C], longer fire season, and expanded vulnerable area of high-elevation forests—are combining to produce the observed increase in wildfire activity."

Schoennagel *et al.* (2007) investigated "climatic mechanisms influencing subalpine forest fire occurrence in western Colorado, which provide a key to the intuitive link between drought and large, high-severity fires that are keystone disturbance processes in many high-elevation forests in the western United States," focusing on three major climatic oscillations: the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO).

They found "fires occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO and [the Pacific Decadal Oscillation (PDO)] and during positive departures from [the mean Atlantic Multidecadal Oscillation (AMO)] index," while "at longer time scales, fires exhibited 20-year periods of synchrony with the cool phase of the PDO, and 80-year periods of synchrony with extreme warm (positive) phases of the AMO." In addition, they note "years of combined positive AMO and negative ENSO and PDO phases represent 'triple whammies' that significantly increased the occurrence of drought-induced fires." On the other hand, they observed "drought and wildfire are associated with warm phases of ENSO and PDO in the Pacific Northwest and northern Rockies while the opposite occurs in the Southwest and southern Rockies," citing the findings of Westerling and Swetnam (2003), McCabe *et al.* (2004), and Schoennagel *et al.* (2005). Schoennagel *et al.* thus concluded "there remains considerable uncertainty regarding the effects of CO₂-induced warming at regional scales." Nevertheless, they reported, "there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies" in the region of their study, high-elevation western U.S. forests, though such a consequence should not necessarily be viewed as a response to CO₂-induced global warming.

Brunelle *et al.* (2010) collected sediments during the summers of 2004 and 2005 from a drainage basin located in southeastern Arizona (USA) and northeastern Sonora (Mexico), from which samples were taken "for charcoal analysis to reconstruct fire

history” as well as pollen data to infer something about climate.

According to the U.S. and Mexican researchers, “preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity,” and the results from the fire reconstruction “show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly.” During this latter period, from approximately AD 900 to 1260, “background charcoal reaches the highest level of the entire record and fire peaks are frequent,” and “the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al.*, 2004).”

Brunelle *et al.* speculated if the region of their study warms in the future, “the role of fire in the desert grasslands is likely to change,” such that “warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires, similar to >5000 cal yr BP.”

Pitkanen *et al.* (2003) constructed a Holocene fire history of dry heath forests in eastern Finland on the basis of charcoal layer data obtained from two small mire basins and fire scars on living and dead pine trees. This work revealed a “decrease in fires during climatic warming in the Atlantic chronozone (about 9000–6000 cal. yr. BP),” prompting them to conclude “the very low fire frequency during the Atlantic chronozone despite climatic warming with higher summer temperatures, is contrary to assumptions about possible implications of the present climatic warming due to greenhouse gasses.” Thereafter, the researchers observed an increase in fire frequency at the transition between the Atlantic and Subboreal chronozones around 6000 cal. yr. BP, noting “the climatic change that triggered the increase in fire frequency was cooling and a shift to a more continental climate.” In addition, they reported the data of Bergeron and Archambault (1993) and Carcaillet *et al.* (2001) from Canada suggest much the same thing; i.e., a decrease in boreal forest fires during periods of greater warmth. Consequently, “as regards the concern that fire frequency will increase in [the] near future owing to global warming,” the researchers say their data “suggest that fires from ‘natural’ causes (lightning) are not likely to increase significantly in eastern Finland and in geographically

and climatically related areas.”

Wallenius *et al.* (2011) observed “the effect of ongoing climate change on forest fires is a hotly debated topic,” with many “experts” arguing “the climatic warming in the 20th and 21st century has resulted and will result in an increase in forest fires.” Against this backdrop Wallenius *et al.* set out to “add information about forest fire history of the as-yet poorly studied *Larix*-dominated forests of central Siberia by means of high-precision dendro-chronological dating of past fires.”

Studying the northern part of the Irkutsk district of central Siberia (centered at approximately 60.75°N, 107.75°E) in areas “untouched by modern forestry and agriculture,” where “population density is low, with less than 0.1 inhabitant per square kilometer,” the group of Finnish, Panamanian, and Russian researchers determined “in the 18th century, on average, 1.9% of the forests burned annually, but in the 20th century, this figure was only 0.6%,” and “the fire cycles for these periods were 52 and 164 years, respectively.” In addition, they reported “a further analysis of the period before the enhanced fire control program in the 1950s revealed a significant lengthening in the fire cycle between the periods 1650–1799 and 1800–1949, from 61 to 152 years, respectively.” They noted “a similar phenomenon has been observed in Fennoscandia, southern Canada and the western United States, where the annually burned proportions have decreased since the 19th century (Niklasson and Granstrom, 2000; Weir *et al.*, 2000; Heyerdahl *et al.*, 2001; Bergeron *et al.*, 2004b).” They also found “in these regions, the decrease has been mostly much steeper, and the current fire cycles are several hundreds or thousands of years.”

Turner *et al.* (2008) analyzed micro-charcoal, pollen, and stable oxygen isotope ($\delta^{18}\text{O}$) data obtained from sediment cores extracted from two crater lake basins in central Turkey, from which they reconstructed synchronized fire, vegetation, and climate histories that extend back in time more than 15,000 years. The authors determined “climatically-induced variation in biomass availability was the main factor controlling the timing of regional fire activity during the Last Glacial-Interglacial climatic transition, and again during Mid-Holocene times, with fire frequency and magnitude increasing during wetter climatic phases.” In addition, they reported spectral analysis of the Holocene part of the record “indicates significant cyclicity with a periodicity of ~1500 years that may be linked with large-scale climate forcing.”

Observations: Extreme Weather

McAneney *et al.* (2009) assembled a much different database for evaluating the global warming/fire relationship as it pertains to Australia. The primary source of information for their study was the “Risk Frontiers’ disaster database of historic building losses—PerilAUS—which provides a reasonably faithful testimony of national building losses from 1900,” with additional information provided by the Insurance Council of Australia’s database of significant insured losses.

The three researchers noted “the annual aggregate numbers of buildings destroyed by bushfire since 1926 ... is 84,” but “most historical losses have taken place in a few extreme fires.” Nevertheless, they observed “the most salient result is that the annual probability of building destruction has remained almost constant over the last century,” even in the face of “large demographic and social changes as well as improvements in fire fighting technique and resources.”

The researchers restated this finding many times: (1) “the historical evidence shows no obvious trend,” (2) “the likelihood of losing homes to bushfire has remained remarkably stable over the last century with some building destruction expected in around 55% of years,” (3) “this same stability is also exhibited for the bigger events with an annual probability of losing more than 25 or 100 homes in a single week remaining around 40% and 20% respectively,” and (4) “the statistics on home destruction have remained obstinately invariant over time.” In addition, McAneney *et al.* noted “Australia’s population has increased from around 4 to 20 million over the last century,” and therefore we might logically have expected “the likelihood of bushfire losses to have increased with population or at least with the population living immediately adjacent to bushlands.” McAneney *et al.* concluded, “despite predictions of an increasing likelihood of conditions favoring bushfires under global climate change, we suspect that building losses due to bushfires are unlikely to alter materially in the near future.”

Although specific areas of the planet experienced both significant increases and decreases in land area burned over the last two or three decades of the twentieth century, as illustrated in the materials reviewed above, what is the case for the world as a whole; i.e., what is the net result of the often opposite wildfire responses to warming that are typical of different parts of the planet?

Girardin *et al.* (2009) investigated “changes in wildfire risk over the 1901–2002 period with an

analysis of broad-scale patterns of drought variability on forested eco-regions of the North American and Eurasian continents.” The seven scientists reported “despite warming since about 1850 and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so (e.g. Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Lehtonen and Kolstrom, 2000; Bergeron *et al.*, 2001, 2004a,b; Mouillot and Field, 2005).” They found “this holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia.”

With respect to this long-term “diminishing fire activity,” Girardin *et al.* observed “the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction.” That role would appear to be one of reducing fire activity. To emphasize that point and provide still more evidence for it, the authors noted, “the fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control.”

Riano *et al.* (2007) conducted “an analysis of the spatial and temporal patterns of global burned area with the Daily Tile US National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer Pathfinder 8 km Land dataset between 1981 and 2000.” As demonstrated previously, for several areas of the world this investigation revealed there were indeed significant upward trends in land area burned. Some parts of Eurasia and western North America, for example, had annual upward trends as high as 24.2 pixels per year, where a pixel represents an area of 64 km². These increases in burned area, however, were offset by equivalent decreases in burned area in tropical Southeast Asia and Central America. Consequently, observed Riano *et al.*, “there was no significant global annual upward or downward trend in burned area.” They also noted “there was also no significant upward or downward global trend in the burned area for any individual month.” In addition, they found “latitude was not determinative, as divergent fire patterns were encountered for various land cover areas at the same latitude.”

In one additional paper providing a global view of the subject, but over a longer time scale, Marlon *et al.* (2008) observed “large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes,” and “climate-

change projections indicate that we will be moving quickly out of the range of the natural variability of the past few centuries.” In an effort to see what the global wildfire “range of natural variability” actually has been, Marlon *et al.* used “sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning [over] the past two millennia.”

The international team of researchers reported “global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870,” after which it “declined abruptly.” In terms of attribution, they said the initial long-term decline in global biomass burning was due to “a long-term global cooling trend,” while they suggested the rise in fires that followed was “linked to increasing human influences.” With respect to the final decline in fires that took place after 1870, however, they noted it occurred “despite increasing air temperatures and population.” As for what may have overpowered the tendency for increased global wildfires that would “normally” have been expected to result from the global warming of the Little Ice Age-to-Current Warm Period transition, the nine scientists attributed “reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management.”

Evidence from prior centuries suggests global warming may indeed have had a tendency to promote wildfires on a global basis (since global cooling had a tendency to reduce them), but technological developments during the industrial age appear to have overpowered this natural tendency. It appears humans have become a dominant factor leading to a decrease in global wildfires over the past century and a half. Although one can readily identify specific parts of the planet that have experienced significant increases or decreases in land area burned over the past several decades, for the globe as a whole there has been no relationship between rising temperatures and total area burned over this latter period.

References

Beaty, R.M. and Taylor, A.H. 2009. A 14,000-year sedimentary charcoal record of fire from the northern Sierra Nevada, Lake Tahoe Basin, California, USA. *The Holocene* **19**: 347–358.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscape on boreal forest fire regime. *Ecology* **72**: 1980–1992.

Bergeron, Y. and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the “Little Ice Age.” *The Holocene* **3**: 255–259.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, E., Leduc, A., Le Goff, H., Lesieur, D., and Logan, K. 2006. Past, current, and future fire frequencies in Quebec’s commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. *Canadian Journal of Forest Research* **36**: 2737–2744.

Bergeron, Y., Flannigan, M., Gauthier, S., Leduc, A., and Lefort, P. 2004a. Past, current and future fire frequency in the Canadian boreal forest: Implications for sustainable forest management. *Ambio* **33**: 356–360.

Bergeron, Y., Gauthier, S., Flannigan, M., and Kafka, V. 2004b. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology* **85**: 1916–1932.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research* **31**: 384–391.

Brunelle, A., Minckley, T.A., Blissett, S., Cobabe, S.K., and Guzman, B.L. 2010. A ~8000 year fire history from an Arizona/Sonora borderland cienega. *Journal of Arid Environments* **24**: 475–481.

Campbell, I.D. and Campbell, C. 2000. Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**: 279–296.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Frechette, B., Gauthier, S., and Prairie, Y. 2001. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime? *Journal of Ecology* **89**: 930–946.

Colombo, S.J., Cherry, M.L., Graham, C., Greifenhagen, S., McAlpine, R.S., Papadopol, C.S., Parker, W.C., Scarr, T., Ter-Mikaelien, M.T., and Flannigan, M.D. 1998. *The Impacts of Climate Change on Ontario’s Forests*. Forest Research Information Paper 143, Ontario Forest Research Institute, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario, Canada.

Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Cwynar, L.C. 1977. Recent history of fire of Barrow Township, Algonquin Park. *Canadian Journal of Botany* **55**: 10–21.

Observations: Extreme Weather

- Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. *Canadian Journal of Botany* **61**: 2459–2471.
- Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hely, C., and Bergeron, Y. 2009. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. *Global Change Biology* **15**: 2751–2769.
- Girardin, M. P., Tardif, J., and Flannigan, M.D. 2006. Temporal variability in area burned for the province of Ontario, Canada, during the past 2000 years inferred from tree rings. *Journal of Geophysical Research* **111**: 10.1029/2005JD006815.
- Hyerdahl, E.K., Brubaker, L.B., and Agee, J.K. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. *Ecology* **82**: 660–678.
- Johnson, E.A., Fryer, G.I., and Heathcott, J.M. 1990. The influence of Man and climate on frequency of fire in the interior wet belt forest, British Columbia. *Journal of Ecology* **78**: 403–412.
- Johnson, E.A. and Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology* **72**: 194–201.
- Larsen, C.P.S. 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1985. *The Holocene* **6**: 449–456.
- Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *Journal of Biogeography* **24**: 663–673.
- Lauzon, E., Kneeshaw, D., and Bergeron, Y. 2007. Reconstruction of fire history (1680–2003) in Gaspesian mixedwood boreal forests of eastern Canada. *Forest Ecology and Management* **244**: 41–49.
- Le Goff, H., Flannigan, M.D., Bergeron, Y., and Girardin, M.P. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. *International Journal of Wildland Fire* **16**: 607–618.
- Lehtonen, H. and Kolstrom, T. 2000. Forest fire history in Viena Karelia, Russia. *Scandinavian Journal of Forest Research* **15**: 585–590.
- Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., and Prentice, I.C. 2008. Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* **1**: 697–702.
- Masters, A.M. 1990. Changes in forest fire frequency in Kootenay National Park, Canadian Rockies. *Canadian Journal of Botany* **68**: 1763–1767.
- McAneney, J., Chen, K., and Pitman, A. 2009. 100-years of Australian bushfire property losses: Is the risk significant and is it increasing? *Journal of Environmental Management* **90**: 2819–2822.
- McCabe, G.J., Palecki, M.A., and Betancourt, J.L. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Sciences (USA)* **101**: 4136–4141.
- Meyer, G.A., Wells, S.G., and Jull, A.J.T. 1995. Fire and alluvial chronology in Yellowstone National Park: Climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**: 1211–1230.
- Mouillot, F. and Field, C.B. 2005. Fire history and the global carbon budget: a 1° x 1° fire history reconstruction for the 20th century. *Global Change Biology* **11**: 398–420.
- Niklasson, M. and Granstrom, A. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology* **81**: 1484–1499.
- Parker, W.C., Colombo, S.J., Cherry, M.L., Flannigan, M.D., Greifenhagen, S., McAlpine, R.S., Papadopol, C., and Scarr, T. 2000. Third millennium forestry: What climate change might mean to forests and forest management in Ontario. *Forest Chronicles* **76**: 445–463.
- Pierce, J.L., Meyer, G.A., and Jull, A.J.T. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* **432**: 87–90.
- Pitkanen, A., Huttunen, P., Jungner, H., Merilainen, J., and Tolonen, K. 2003. Holocene fire history of middle boreal pine forest sites in eastern Finland. *Annales Botanici Fennici* **40**: 15–33.
- Podur, J., Martell, D.L., and Knight, K. 2002. Statistical quality control analysis of forest fire activity in Canada. *Canadian Journal of Forest Research* **32**: 195–205.
- Riano, D., Moreno Ruiz, J.A., Isidoro, D., and Ustin, S.L. 2007. Global spatial patterns and temporal trends of burned area between 1981 and 2000 using NOAA-NASA Pathfinder. *Global Change Biology* **13**: 40–50.
- Rollins, M.G., Morgan, P., and Swetnam, T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. *Landscape Ecology* **17**: 539–557.
- Running, S.W. 2006. Is global warming causing more, larger wildfires? *Scienceexpress* 6 July 2006 10.1126/science.1130370.
- Schoennagel, T., Veblen, T.T., Kulakowski, D., and Holz, A. 2007. Multidecadal climate variability and climate interactions affect subalpine fire occurrence, western Colorado (USA). *Ecology* **88**: 2891–2902.
- Schoennagel, T., Veblen, T.T., Romme, W.H., Sibold, J.S.,

and Cook, E.R. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. *Ecological Applications* **15**: 2000–2014.

Stine, S. 1998. In: Issar, A.S. and Brown, N. (Eds.) *Water, Environment and Society in Times of Climatic Change*. Kluwer, Dordrecht, The Netherlands, pp. 43–67.

Tardif, J. 2004. *Fire History in the Duck Mountain Provincial Forest, Western Manitoba*. Sustainable Forest Management Network, University of Alberta, Edmonton, Alberta, Canada.

Turner, R., Roberts, N., and Jones, M.D. 2008. Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. *Global and Planetary Change* **63**: 317–324.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**: 220–227.

Wallenius, T., Larjavaara, M., Heikkinen, J., and Shibistova, O. 2011. Declining fires in Larix-dominated forests in northern Irkutsk district. *International Journal of Wildland Fire* **20**: 248–254.

Weir, J.M.H., Johnson, E.A., and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecological Applications* **10**: 1162–1177.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. 2006. Warming and earlier spring increases western U.S. Forest wildfire activity. *Scienceexpress* 6 July 2006 10.1126/science.1128834.

Westerling, A.L. and Swetnam, T.W. 2003. Interannual to decadal drought and wildfire in the western United States. *EOS: Transactions, American Geophysical Union* **84**: 545–560.

Whitlock, C., Shafer, S.L., and Marlon, J. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management* **178**: 163–181.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

Wotton, B.M. and Flanagan, M.D. 1993. Length of the fire season in a changing climate. *Forest Chronicles* **69**: 187–192.

7.4 Drought

One of the many assumed dangers of global warming is the predicted propensity for rising temperatures to

produce more frequent, more severe, and longer-lasting droughts almost everywhere on Earth. In its most recent assessment report, the IPCC presents the following statements regarding the attribution of historic drought to human-induced global warming:

While the [Fourth Assessment Report] concluded that it is more likely than not that anthropogenic influence has contributed to an increase in the droughts observed in the second half of the 20th century, an updated assessment of the observational evidence indicates that the AR4 conclusions regarding global increasing trends in hydrological droughts since the 1970s are no longer supported. Owing to the low confidence in observed large-scale trends in dryness combined with difficulties in distinguishing decadal-scale variability in drought from long term climate change we now conclude there is low confidence in the attribution of changes in drought over global land since the mid-20th century to human influence (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 31).

The current assessment does not support the [Fourth Assessment Report] conclusions regarding global increasing trends in droughts but rather concludes that there is not enough evidence at present to suggest high confidence in observed trends in dryness. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 61).

Although the IPCC has revised downward its confidence in the attribution of historical drought to rising CO₂ emissions, it is doing so because the IPCC claims it has little confidence in the observed data trends and not enough data exist to validate its model-based theory on drought.

Section 7.4 presents a comprehensive analysis of the observational data on drought, demonstrating there exists a large body of peer-reviewed science that invalidates the model-based claims of global warming causing more drought.

7.4.1 Africa

Data presented in numerous peer-reviewed studies do not support the model-based claim CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Africa.

In “A multimodel study of the twentieth-century

Observations: Extreme Weather

simulations of Sahel drought from the 1970s to 1990s,” Lau *et al.* (2006) explored “the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs [coupled general circulation models] that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4.” The scientists examined 19 CGCMs, each of which was “driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions.” The work revealed “only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal.” In addition, the scientists reported “even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events.”

Since all 19 CGCMs used in preparing the IPCC’s *Fourth Assessment Report* were unable to adequately simulate the basic characteristics of what Lau *et al.* call one of the past century’s “most pronounced signals of climate change,” this failure of what they call an “ideal test” for evaluating the models’ abilities to accurately simulate “long-term drought” and “coupled atmosphere-ocean-land processes and their interactions” suggests extreme caution in relying on any of the models’ output as a guide to the future. Even though the models were “driven by combinations of realistic prescribed external forcing,” they could not properly simulate even the recent past.

Shifting attention to instrumental and proxy drought records, Nicholson (2001) reported in a review of information pertaining to the past two centuries there has been “a long-term reduction in rainfall in the semi-arid regions of West Africa” that has been “on the order of 20 to 40% in parts of the Sahel.” Describing the phenomenon as “three decades of protracted aridity,” she observed “nearly all of Africa has been affected ... particularly since the 1980s.” Nevertheless, Nicholson reported “rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented” and “a similar dry episode prevailed during most of the first half of the 19th century,” when much of the planet was still experiencing Little Ice Age conditions.

Therrell *et al.* (2006) developed “the first tree-

ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe.” This revealed “a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995),” and “an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data.” They reported, for example, the year 1860 (the most droughty year of the entire period) was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as “a season of ‘severe and universal drought’ with ‘food of every description’ being ‘exceedingly scarce’ and the losses of cattle being ‘very severe’ (Nash and Endfield, 2002).” At the other end of the moisture spectrum, Therrell *et al.* reported “a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era.” Consequently, for a large part of central southern Africa, the supposedly unprecedented global warming of the twentieth century did not result in an intensification of either extreme dry or wet periods. If anything, just the opposite appears to have occurred.

Esper *et al.* (2007) reported similar findings, noting “analysis of the PDSI [Palmer Drought Severity Index], a standardized measure of surface moisture conditions, revealed distinct 20th century aridity changes in vulnerable NW Africa, including a sharp downward trend towards drier conditions in the 1980s (Luterbacher *et al.*, 2006),” but “a high-resolution long-term reconstruction that could place current conditions in the context of the past millennium is missing for N Africa,” which the authors set out to develop. Esper *et al.* “re-use *Cedrus atlantica* tree-ring data generated in the 1980s (Glueck and Stockton, 2001) and combine these measurements with a major update collected in 2002,” which “allows analysis of tree growth and instrumental data during the current drought episode in comparison to PDSI estimates back to AD 1049.”

The six scientists reported “PDSI values were above average for most of the 1450–1980 period, which let recent drought appear exceptional.” However, they found the long-term results they obtained indicated the “pluvial episode of the past millennium was preceded by generally drier conditions back to 1049,” leading them to state the late twentieth century drought “appears more typical when associated with conditions before 1400.” In

addition, they concluded, the “ultimate drivers” for the medieval hydroclimate pattern that led to the earlier drought conditions in Morocco “seemed to be high solar irradiance and low volcanic forcings (Emile-Geay *et al.*, 2007).”

Verschuren *et al.* (2000) developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on level and salinity fluctuations of a small crater-lake in Kenya, using data derived from diatom and midge assemblages retrieved from the lake’s sediments. They found the Little Ice Age was generally wetter than the Modern Warm Period, but they identified three intervals of prolonged dryness within the Little Ice Age (1390–1420, 1560–1625, and 1760–1840). They note these “episodes of persistent aridity” were “more severe than any recorded drought of the twentieth century.”

Holmes *et al.* (1997) probed 1,500 years into the past, reporting the African Sahel since the late 1960s has experienced “one of the most persistent droughts recorded by the entire global meteorological record.” In a high-resolution study of a sediment sequence extracted from an oasis in the Manga Grasslands of northeast Nigeria, they determined “the present drought is not unique and that drought has recurred on a centennial to interdecadal timescale during the last 1500 years.”

Russell *et al.* (2007) added another 500 years to the analysis, conducting lithostratigraphic analyses of sediment cores obtained from two crater lake basins in Western Uganda, Africa—Lake Kitagata (0°03'S, 29°58'E) and Lake Kibengo (0°04.9'S, 30°10.7'E)—spanning the past two millennia. Among other things, Russell *et al.* reported “variations in sedimentation and salt mineralogy of hypersaline Lake Kitagata, and a succession of fine-grained lake sediments and peat in the freshwater Lake Kibengo, suggest century-scale droughts centered on AD ~0 [and] ~1100.”

Discussing what they called the “broader climatic implications” of their findings, the three researchers reported “based on comparison of proxy water-balance records from Lakes Edward (Russell *et al.*, 2003; Russell and Johnson, 2005), Naivasha (Verschuren *et al.*, 2000), Turkana (Halfman *et al.*, 1994), and Tanganyika (Alin and Cohen, 2003), Russell *et al.* (2003) argued that drought around 2000 years ago (AD ~0) affected ‘much, if not all, of equatorial Africa.’” Similarly, they observed, “Verschuren (2004) argued that drought centered on AD 1150 affected much of the region, a hypothesis supported by Russell and Johnson (2005).”

Consequently, and in light of their similar, newer results, the three scientists concluded “droughts at AD ~0 and ~1150”—which roughly mark the midpoints of the Roman and Medieval Warm Periods, respectively—“do appear to have affected much of equatorial Africa.”

Russell and Johnson (2005) derived a detailed precipitation history from sediment cores retrieved from Lake Edward, the smallest of the great rift lakes of East Africa, located on the border that separates Uganda and the Democratic Republic of the Congo. They discovered from the start of the record almost 5,500 years ago until approximately 1,800 years ago, there was a long-term trend toward progressively more arid conditions, after which there followed a “slight trend” toward wetter conditions that has persisted to the present. Superimposed on these long-term trends were major droughts of “at least century-scale duration,” centered at approximately 850, 1,500, 2,000, and 4,100 years ago.

The studies cited here make clear the need for long-term (millennial-scale) records of climatic and meteorological phenomena in order to determine how exceptional twentieth century changes in their characteristics might be, which can help determine whether there is compelling reason to attribute such changes to historical increases in the atmospheric concentrations of greenhouse gases. For Africa, real-world evidence suggests the global warming of the past century or so has not led to a greater frequency or severity of drought in that part of the world. Even the continent’s worst drought in recorded meteorological history does not seem to have been any worse (in fact, it was much milder) than droughts that occurred in the historic past. There is little reason to expect global warming to lead to more frequent or severe droughts in Africa.

References

- Alin, S.R. and Cohen, A.S. 2003. Lake-level history of Lake Tanganyika, East Africa, for the past 2500 years based on ostracode-inferred water-depth reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology* **199**: 31–49.
- Emile-Geay, J., Cane, M., Seager, R., Kaplan, A., and Almasi, P. 2007. El Niño as a mediator of the solar influence on climate. *Paleoceanography* **22**: 10.1029/2006PA001304.
- Esper, J., Frank, D., Buntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E. 2007. Long-term drought

Observations: Extreme Weather

severity variations in Morocco. *Geophysical Research Letters* **34**: 10.1029/2007GL030844.

Glueck, M.F. and Stockton, C.W. 2001. Reconstruction of the North Atlantic Oscillation, 1429-1983. *International Journal of Climatology* **21**: 1453–1465.

Halfman, J.D., Johnson, T.C., and Finney, B. 1994. New AMS dates, stratigraphic correlations and decadal climate cycles for the past 4 ka at Lake Turkana, Kenya. *Palaeogeography, Palaeoclimatology, Palaeoecology* **111**: 83–98.

Holmes, J.A., Street-Perrott, F.A., Allen, M.J., Fothergill, P.A., Harkness, D.D., Droon, D., and Perrott, R.A. 1997. Holocene palaeolimnology of Kajemaru Oasis, Northern Nigeria: An isotopic study of ostracodes, bulk carbonate and organic carbon. *Journal of the Geological Society, London* **154**: 311–319.

Lau, K.M., Shen, S.S.P., Kim, K.-M., and Wang, H. 2006. A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s. *Journal of Geophysical Research* **111**: 10.1029/2005JD006281.

Luterbacher, J., *et al.* 2006. Mediterranean climate variability over the last centuries: A review. In: Lionello, P., *et al.* (Eds.) *The Mediterranean Climate*, Elsevier, Amsterdam, The Netherlands, pp. 27–148.

Nash, D.J. and Endfield, G.H. 2002. A 19th-century climate chronology for the Kalahari region of central southern Africa derived from missionary correspondence. *International Journal of Climatology* **22**: 821–841.

Nicholson, S.E. 2001. Climatic and environmental change in Africa during the last two centuries. *Climate Research* **17**: 123–144.

Russell, J.M. and Johnson, T.C. 2005. A high-resolution geochemical record from Lake Edward, Uganda-Congo, and the timing and causes of tropical African drought during the late Holocene. *Quaternary Science Reviews* **24**: 1375–1389.

Russell, J.M., Johnson, T.C., Kelts, K.R., Laerdal, T., and Talbot, M.R. 2003. An 11,000-year lithostratigraphic and paleohydrologic record from Equatorial Africa: Lake Edward, Uganda-Congo. *Palaeogeography, Palaeoclimatology, Palaeoecology* **193**: 25–49.

Russell, J.M., Verschuren, D., and Eggermont, H. 2007. Spatial complexity of “Little Ice Age” climate in East Africa: sedimentary records from two crater lake basins in western Uganda. *The Holocene* **17**: 183–193.

Therrell, M.D., Stahle, D.W., Ries, L.P., and Shugart, H.H. 2006. Tree-ring reconstructed rainfall variability in Zimbabwe. *Climate Dynamics* **26**: 677–685.

Verschuren, D. 2004. Decadal and century-scale climate

variability in tropical Africa during the past 2,000 years. In: Battarbee, R.W. (Ed.) *Past Climate Variability through Europe and Africa*. Paleoenvironmental Research Book Series, Elsevier.

Verschuren, D., Laird, K.R., and Cumming, B. 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. *Nature* **403**: 410–414.

Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

7.4.2 Asia

As noted in the introduction to this Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Asia.

Using a multimodel approach developed previously (Wang *et al.*, 2009), Wang *et al.* (2011) employed four physically based land surface hydrology models driven by an observation-based three-hourly meteorological dataset to simulate soil moisture over China for the period 1950–2006, deriving monthly values of total column soil moisture from which they calculated agricultural drought severities and durations. The authors reported “for drought areas greater than 150,000 km² and durations longer than three months, a total of 76 droughts were identified,” and “regions with downward trends were larger than those with upward trends (37% versus 26% of the land area),” implying “over the period of analysis, the country has become slightly drier in terms of soil moisture.”

Wang *et al.*’s findings are not proof of a CO₂-induced temperature link, nor do they imply an increase in future drought. Any suggestion of a link between drought and global warming is unique to the Wang *et al.* study, perhaps because their drought calculations are derived from models simulating soil moisture as opposed to measuring it. With respect to the future, Wang *et al.* report “climate models project that a warmer and moister atmosphere in the future will actually lead to an enhancement of the circulation strength and precipitation of the summer monsoon over most of China (e.g., Sun and Ding, 2010) that will offset enhanced drying due to increased atmospheric evaporative demand in a warmer world (Sheffield and Wood, 2008).”

Tao and Zhang (2011) provide some support for

this statement. Using the Lund-Potsdam-Jena Dynamic Global Vegetation Model, they concluded the net effect of physiological and structural vegetation responses to expected increases in the air's CO₂ content will lead to "a decrease in mean evapotranspiration, as well as an increase in mean soil moisture and runoff across China's terrestrial ecosystem in the 21st century," which should act to lessen, or even offset, the "slightly drier" soil moisture conditions modeled by Wang *et al.*

In other studies examining drought trends in Asia—and China in particular—Paulsen *et al.* (2003) employed high-resolution stalagmite records of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from Buddha Cave "to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." Their record began in the depths of the Dark Ages Cold Period, which ended approximately AD 965 with the commencement of the Medieval Warm Period, and continued to approximately AD 1475, whereupon the Little Ice Age set in and held sway until about AD 1825, after which the warming responsible for the Modern Warm Period began.

With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet. It was followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Modern Warm Period. Paulsen *et al.*'s data also revealed other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture, and they attributed most of these higher-frequency cycles to solar phenomena. The authors concluded the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

The authors' data indicated Earth's climate is determined by a conglomerate of cycles within cycles, all of which are essentially independent of the air's CO₂ concentration. The data also demonstrated the multicentury warm and cold periods of the planet's millennial-scale oscillation of temperature may have both wetter and drier periods embedded within them. Consequently, warmth alone is not a sufficient condition for the occurrence of the dryness associated with drought.

Jiang *et al.* (2005) analyzed historical documents to produce a time series of flood and drought occurrences in eastern China's Yangtze Delta since AD 1000. They found alternating wet and dry episodes throughout this lengthy period, and the data demonstrated droughts and floods usually occurred in the spring and autumn seasons of the same year, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850), as opposed to the preceding Medieval Warm Period and the following Current Warm Period.

Zhang *et al.* (2007) developed for China's Yangtze Delta region flood and drought histories of the past thousand years based on "local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." They described this as "a powerful way to characterize the frequency, the intensity, the time position, and the duration of variations in a climate data series." They also compared their results with two 1,000-year temperature histories of the Tibetan Plateau, encompassing northeastern Tibet and southern Tibet.

Zhang *et al.* reported during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they reported during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

Zhang *et al.* (2009) utilized the decadal locust (*Locusta migratoria manilensis*) abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al.* (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al.* (2002) for the AD 950s–1950s to perform a wavelet analysis "to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China." The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods

promoted locust plagues by enhancing temperature-associated drought/flood events.

The six scientists observed “global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China,” noting these findings “challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects.” They reported their results are an example of “benign effects of global warming on the regional risk of natural disasters.”

Davi *et al.* (2006) employed absolutely dated tree-ring-width chronologies from five sampling sites in the west-central region of Mongolia—all “in or near the Selenge River basin, the largest river in Mongolia”—to develop a reconstruction of stream-flow that extended from 1637 to 1997. Of the 10 driest five-year periods of the 360-year record, they found only one occurred during the twentieth century (and that just barely: 1901–1905, sixth driest of the 10 extreme periods), and of the 10 wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the 10 extreme periods, respectively). Consequently, “there is much wider variation in the long-term tree-ring record than in the limited record of measured precipitation,” such that over the course of the twentieth century, which the IPCC describes as having experienced a warming unprecedented over the past one to two millennia, extremes of both dryness and wetness were less frequent and less severe.

Kalugin *et al.* (2005) utilized sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia to produce a multiproxy climate record spanning the past 800 years. This record revealed the regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, however, temperatures cooled and productivity dropped, reaching a broad minimum between 1660 and 1700. This interval “corresponds to the age range of the well-known Maunder Minimum (1645–1715)” and is “in agreement with the timing of the Little Ice Age in Europe (1560–1850).”

With respect to moisture and precipitation, Kalugin *et al.* reported the period between 1210 and 1480 was more humid than today, and the period between 1480 and 1840 was more arid. In addition, they reported three episodes of multiyear drought (1580–1600, 1665–1690, and 1785–1810). These findings are in agreement with other historical data

and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al.*, 1996; Panyushkina *et al.*, 2000). All of the major multiyear droughts detected in this study occurred during the cool phase of the 800-year record.

Kim *et al.* (2009) developed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006), along with the results of a number of “progressive methods for assessing drought severity from diverse points of view,” including the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), which Kim *et al.* describe as “an intensive measure that considers daily water accumulation with a weighting function for time passage”; a Corrected EDI that “considers the rapid runoff of water resources after heavy rainfall” (CEDI); an Accumulated EDI that “considers the drought severity and duration of individual drought events” (AEDI); and a year-accumulated negative EDI “representing annual drought severity” (YAEDI).

The researchers’ precipitation history and two of their drought severity histories are presented, in that order, in Figures 7.4.2.1 and 7.4.2.2.

The figures clearly show the only major multiyear deviation from long-term normalcy is the decadal-scale decrease in precipitation and ensuing drought, each of which achieved their most extreme values (low in the case of precipitation, high in the case of drought) in the vicinity of AD 1900, well before the twentieth century rise in atmospheric CO₂ and global temperatures. The significant post-Little Ice Age warming of the planet thus had essentially no effect on the long-term histories of either precipitation or drought at Seoul, Korea, adding to the growing body of such findings throughout Asia.

Touchan *et al.* (2003) developed two reconstructions of spring precipitation for southwestern Turkey from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia*, and *Pinus nigra*, and the other one (1339–1998) based on three chronologies of *Juniperus excelsa*. The records “show clear evidence of multi-year to decadal variations in spring precipitation.” Nevertheless, the researchers reported “dry periods of 1–2 years were well distributed throughout the record” and the same was largely true of wet periods. With respect to more extreme events, the period preceding the industrial revolution stood out. They note, for example, “all of the wettest 5-year periods occurred prior to 1756.” The longest period of reconstructed spring drought was the four-year period 1476–1479, and the single

Climate Change Reconsidered II

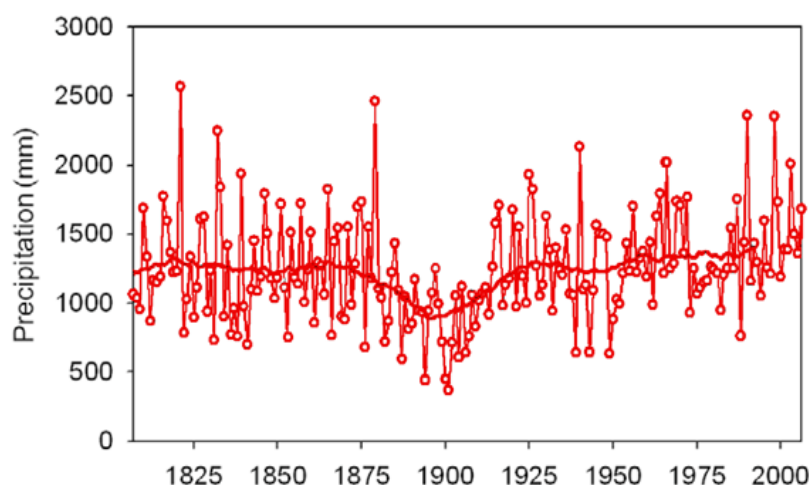


Figure 7.4.2.1. Annual precipitation history at Seoul, Korea, where the solid line represents a 30-year moving-average. Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

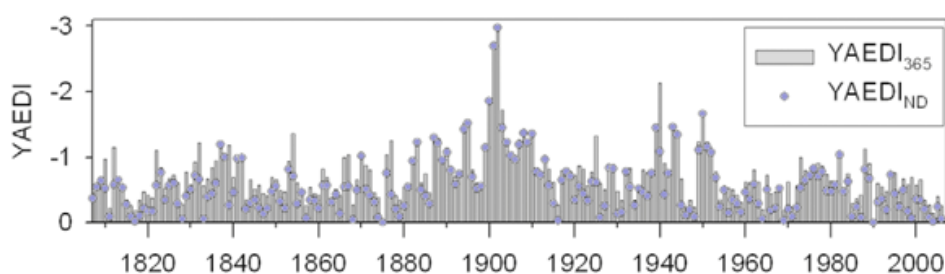


Figure 7.4.2.2. Annual “dryness” history at Seoul, Korea, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12..

driest spring was 1746.

Sinha *et al.* (2007) derived a nearly annually resolved record of Indian summer monsoon (ISM) rainfall variations for the core monsoon region of India from AD 600 to 1500 based on a ^{230}Th -dated stalagmite oxygen isotope record from Dandak Cave, located at 19°00'N, 82°00'E. The authors noted “the short instrumental record of ISM under-estimates the magnitude of monsoon rainfall variability” and “nearly every major famine in India [over the period of their study] coincided with a period of reduced monsoon rainfall as reflected in the Dandak $\delta^{18}\text{O}$ record.” They found two particularly devastating famines “occurred at the beginning of the Little Ice

Age during the longest duration and most severe ISM weakening of [their] reconstruction.” they also observed “ISM reconstructions from Arabian Sea marine sediments (Agnihotri *et al.*, 2002; Gupta *et al.*, 2003; von Rad *et al.*, 1999), stalagmite $\delta^{18}\text{O}$ records from Oman and Yemen (Burns *et al.*, 2002; Fleitmann *et al.*, 2007) and a pollen record from the western Himalaya (Phadtare and Pant, 2006) also indicate a weaker monsoon during the Little Ice Age and a relatively stronger monsoon during the Medieval Warm Period.” The eight researchers noted “since the end of the Little Ice Age, ca 1850 AD, the human population in the Indian monsoon region has increased from about 200 million to over 1 billion,” and “a recurrence of weaker intervals of ISM comparable to those inferred in our record would have serious implications to human health and economic sustainability in the region.”

Sinha *et al.* (2011) warned the return of a severe drought to India could pose a “serious threat for the predominantly agrarian-based societies of monsoon Asia, where the lives of billions of people are tightly intertwined with the annual monsoon cycle.” The eight researchers from China, Germany, and the United States reviewed the history of the monsoon, relying heavily on the work of Sinha *et al.* (2007) and Berkelhammer *et al.* (2010).

Sinha *et al.* (2011) observed “proxy reconstructions of precipitation from central India, north-central China [Zhang *et al.*, 2008], and southern Vietnam [Buckley *et al.*, 2010] reveal a series of monsoon droughts during the mid 14th-15th centuries

that each lasted for several years to decades,” and “these monsoon megadroughts have no analog during the instrumental period.” They noted “emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley *et al.*, 2007; Sano *et al.*, 2009) and India (Borgaonkar *et al.*, 2010) suggest that the mid 14th-15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the Little Ice Age” and “appear to have played a major role in shaping significant regional societal changes at that time.” Among these upheavals, they made special mention of “famines and significant political reorganization within India (Dando, 1980; Pant *et al.*, 1993; Maharatna, 1996), the collapse of the Yuan dynasty in China (Zhang *et al.*, 2008), the Rajarata civilization in Sri Lanka (Indrapala, 1971), and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley *et al.*, 2010),” noting the evidence suggests “monsoon megadroughts may have played a major contributing role in shaping these societal changes.”

Cluis and Laberge (2001) analyzed streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any changes in Asian river runoff of the type the IPCC predicted would lead to more frequent and more severe drought. They based their study on the streamflow histories of 78 rivers said to be “geographically distributed throughout the whole Asia-Pacific region.” The mean start and end dates of these series were 1936 ± 5 years and 1988 ± 1 year, respectively, representing an approximate half-century timespan.

With respect to the rivers’ annual minimum discharges, which is the measure associated with drought, the authors found 53% were unchanged over the period of the study. Where there were trends, 62% of them were upward, indicative of a growing likelihood of less frequent and less severe drought.

References

Agnihotri, R., Dutta, K., Bhushan, R., and Somayajulu, B.L.K. 2002. Evidence for solar forcing on the Indian monsoon during the last millennium. *Earth and Planetary Science Letters* **198**: 521–527.

Berkelhammer, M., Sinha, A., Mudelsee, M., and Cannariato, K.G. 2010. Persistent multidecadal power in the Indian summer monsoon. *Earth and Planetary Science Letters* **290**: 166–172.

Borgaonkar, H.P., Sikdera, A.B., Rama, S., and Panta, G.B.

2010. El Niño and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L.F.) trees from south India. *Palaeogeography, Palaeoclimatology, Palaeoecology* **285**: 74–84.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Nam, L.C., Wichienkeo, A., Minh, T.T., and Hong, T.M. 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences USA* **107**: 6748–6752.

Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P., and Prasomsin, P. 2007. Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. *Climate Dynamics* **29**: 63–71.

Burns, S.J., Fleitmann, D., Mudelsee, M., Neff, U., Matter, A., and Mangini, A. 2002. A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. *Journal of Geophysical Research* **107**: 10.1029/2001JD001281.

Butvilovskii, V.V. 1993. *Paleogeography of the Late Glacial and Holocene on Altai*. Tomsk University, Tomsk.

Byun, H.R. and Wilhite, D.A. 1999. Objective quantification of drought severity and duration. *Journal of Climate* **12**: 2747–2756.

Cluis, D. and Laberge, C. 2001. Climate change and trend detection in selected rivers within the Asia-Pacific region. *Water International* **26**: 411–424.

Dando, W.A. 1980. *The Geography of Famine*. John Wiley, New York, New York, USA, p. 209.

Davi, N.K., Jacoby, G.C., Curtis, A.E., and Baatarbileg, N. 2006. Extension of drought records for central Asia using tree rings: West-Central Mongolia. *Journal of Climate* **19**: 288–299.

Fleitmann, D., Burns, S.J., Mangini, A., Mudelsee, M., Kramers, J., Neff, U., Al-Subbary, A.A., Buettner, A., Hippler, D., and Matter, A. 2007. Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). *Quaternary Science Reviews* **26**: 170–188.

Gupta, A.K., Anderson, D.M., and Overpeck, J.T. 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. *Nature* **421**: 354–356.

Indrapala, K. 1971. *The Collapse of the Rajarata Civilization and the Drift to the Southwest*. University of Ceylon Press.

Jacoby, G.C., D’Arrigo, R.D., and Davaajats, T. 1996. Mongolian tree rings and 20th century warming. *Science* **273**: 771–773.

Climate Change Reconsidered II

- Jiang, T., Zhang, Q., Blender, R., and Fraedrich, K. 2005. Yangtze Delta floods and droughts of the last millennium: Abrupt changes and long term memory. *Theoretical and Applied Climatology* **82**: 131–141.
- Kalugin, I., Selegei, V., Goldberg, E., and Seret, G. 2005. Rhythmic fine-grained sediment deposition in Lake Teletskoye, Altai, Siberia, in relation to regional climate change. *Quaternary International* **136**: 5–13.
- Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.
- Ma, S. 1958. The population dynamics of the oriental migratory locust (*Locusta migratoria manilensis* Meyen) in China. *Acta Entomologica Sinica* **8**: 1–40.
- Maharatna, A. 1996. *The Demography of Famines: An Indian Historical Perspective*. Oxford University Press, Delhi, India, p. 317.
- Pant, G.B., Rupa-Kumar, K.N., Sontakke, A., and Borgaonkar, H.P. 1993. Climate variability over India on century and longer time scales. In: Keshavamurthy, R.N. and Joshi, P.C. (Eds.) *Tropical Meteorology*. Tata McGraw-Hill, New Delhi, India, pp. 149–158.
- Panyushkina, I.P., Adamenko, M.F., Ovchinnikov, D.V. 2000. Dendroclimatic net over Altai Mountains as a base for numerical paleogeographic reconstruction of climate with high time resolution. In: *Problems of Climatic Reconstructions in Pleistocene and Holocene 2*. Institute of Archaeology and Ethnography, Novosibirsk, pp. 413–419.
- Paulsen, D.E., Li, H.-C., and Ku, T.-L. 2003. Climate variability in central China over the last 1270 years revealed by high-resolution stalagmite records. *Quaternary Science Reviews* **22**: 691–701.
- Phadtare, N.R. and Pant, R.K. 2006. A century-scale pollen record of vegetation and climate history during the past 3500 years in the Pinder Valley, Kumaon Higher Himalaya, India. *Journal of the Geological Society of India* **68**: 495–506.
- Sano, M., Buckley, B.M., and Sweda, T. 2009. Tree-ring based hydroclimate reconstruction over northern Vietnam from *Fokienia hodginsii*: eighteenth century mega-drought and tropical Pacific influence. *Climate Dynamics* **33**: 331–340.
- Sheffield, J. and Wood, E.F. 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics* **31**: 79–105.
- Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R., and Singh, I.B. 2007. A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India. *Geophysical Research Letters* **34**: 10.1029/2007GL030431.
- Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R.L., Buckley, B., Aldenderfer, M., and Mudelsee, M. 2011. A global context for megadroughts in monsoon Asia during the past millennium. *Quaternary Science Reviews* **30**: 47–62.
- Sun, Y. and Ding, Y.-H. 2010. A projection of future changes in summer precipitation and monsoon in East Asia. *Science in China Series D: Earth Sciences* **53**: 284–300.
- Tao, F. and Zhang, Z. 2011. Dynamic response of terrestrial hydrological cycles and plant water stress to climate change in China. *Journal of Hydrometeorology* **12**: 371–393.
- Touchan, R., Garfin, G.M., Meko, D.M., Funkhouser, G., Erkan, N., Hughes, M.K., and Wallin, B.S. 2003. Preliminary reconstructions of spring precipitation in southwestern Turkey from tree-ring width. *International Journal of Climatology* **23**: 157–171.
- von Rad, U., Michels, K.H., Schulz, H., Berger, W.H., and Sirocko, F. 1999. A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, northeastern Arabian Sea. *Quaternary Research* **51**: 39–53.
- Wang, A., Bohn, T.J., Mahanama, S.P., Koster, R.D., and Lettenmaier, D.P. 2009. Multimodel ensemble reconstruction of drought over the continental United States. *Journal of Climate* **22**: 2694–2712.
- Wang, A., Lettenmaier, D.P., and Sheffield, J. 2011. Soil moisture drought in China, 1950–2006. *Journal of Climate* **24**: 3257–3271.
- Yang, B., Brauning, A., Johnson, K.R., and Yafeng, S. 2002. Temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 10.1029/2001GL014485.
- Zhang, P.Z., Cheng, H., Edwards, R.L., Chen, F.H., Wang, Y.J., Yang, X.L., Liu, J., Tan, M., Wang, X.F., Liu, J.H., An, C.L., Dai, Z.B., Zhou, J., Zhang, D.Z., Jia, J.H., Jin, L.Y., and Johnson, K.R. 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* **322**: 940–942.
- Zhang, Q., Chen, J., and Becker, S. 2007. Flood/drought change of last millennium in the Yangtze Delta and its possible connections with Tibetan climatic changes. *Global and Planetary Change* **57**: 213–221.
- Zhang, Z., Cazelles, B., Tian, H., Stige, L.C., Brauning, A.,

and Stenseth, N.C. 2009. Periodic temperature-associated drought/flood drives locust plagues in China. *Proceedings of the Royal Society B* **276**: 823–831.

7.4.3 Europe

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Europe.

Noting “the media often reflect the view that recent severe drought events are signs that the climate has in fact already changed owing to human impacts,” Hisdal *et al.* (2001) performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and frequency of drought over the four time periods 1962–1990, 1962–1995, 1930–1995, and 1911–1995. This work revealed “despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied.” To the contrary, they found “overall, the number of negative significant trends pointing towards decreasing drought deficit volumes or fewer drought events exceeded the number of positive significant trends (increasing drought deficit volumes or more drought events).”

Linderholm and Chen (2005) derived a 500-year history of winter (September–April) precipitation from tree-ring data obtained within the Northern Boreal zone of Central Scandinavia. This chronology indicated below-average precipitation occurred during the periods 1504–1520, 1562–1625, 1648–1669, 1696–1731, 1852–1871, and 1893–1958, with the lowest values occurring at the beginning of the record and at the beginning of the seventeenth century. For this portion of the European continent, twentieth century global warming did not result in more frequent or more severe droughts.

Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer’s diary, to produce a 250-year record of summer (June–August) precipitation in east central Sweden. They found a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record, with the past century exhibiting less

variability than the preceding 150 years. A persistent dry episode stood out vividly between 1806 and 1832, when the tree-ring history revealed its longest consecutive period of below-average tree growth, which was associated with a concomitant period of drought documented in the farmer’s diary.

Korhonen and Kuusisto (2010) observed “annual mean temperatures in Finland increased by about 0.7°C during the 20th century,” citing Jylha *et al.* (2004), while noting under such a warming regime, “both droughts and floods are expected to intensify,” a claim made by the IPCC. In a study designed to explore the soundness of this contention, the authors analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland up to the year 2004, using data supplied by the Finnish Environment Institute.

They found as “winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites.” They note “the magnitudes of spring high flow have not changed,” but low flows “have increased at about half of the unregulated sites due to an increase in both winter and summer discharges.” They reported “statistically significant overall changes have not been observed in mean annual discharge.”

Here too, Earth did not behave according to the model projections, in this case regarding hydrological responses to global warming. The conflict occurred at both ends of the available moisture spectrum. At the high end, there was no change in the magnitude of flows that can lead to flooding. At the low end, there was an increase in flow magnitude, which either acts to prevent droughts or leads to less frequent and/or less severe episodes of it.

Wilson *et al.* (2005) used the regional curve standardization technique to develop a summer (March–August) precipitation chronology from living and historical ring-widths of trees in the Bavarian Forest region of southeast Germany for the period 1456–2001. This technique captured low frequency variations indicating the region was substantially drier than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870, all intervals much colder than the bulk of the twentieth century.

In the Danube River in western Europe, several researchers studied the precipitation histories of adjacent regions and suggested an anthropogenic signal was present in the latter decades of the twentieth century, attributing that period’s supposedly drier conditions to that anthropogenic signal. Ducic

(2005) examined those claims by analyzing observed and reconstructed discharge rates of the river near Orsova, Serbia over the period 1731–1990. Ducic found the lowest 5-year discharge value in the preinstrumental era (1831–1835) was practically equal to the lowest 5-year discharge value in the instrumental era (1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Ducic also reported the discharge rate for the last decade of the record (1981–1990), which prior researchers claimed was anthropogenically influenced, was “completely inside the limits of the whole series” and only 0.7% less than the 260-year mean. The scientist concluded “modern discharge fluctuations do not point to dominant anthropogenic influence.” Ducic also concluded the detected cyclicity in the record could “point to the domination of the influence of solar activity.”

van der Schrier *et al.* (2006) constructed monthly maps of the Self-Calibrating Palmer Drought Severity Index (SC-PDSI, a variant put forward by Wells *et al.* (2004) of the more common PDSI) for the period 1901–2002 for Europe (35°N–70°N, 10°W–60°E). This index “improves upon the PDSI by maintaining consistent behavior of the index over diverse climatological regions,” which “makes spatial comparisons of SC-PDSI values on continental scales more meaningful.”

The scientists found “over the region as a whole, the mid-1940s to early 1950s stand out as a persistent and exceptionally dry period, whereas the mid-1910s and late 1970s to early 1980s were very wet.” Over the entire study period, they found trends in the continent’s summer moisture availability “fail to be statistically significant, both in terms of spatial means of the drought index and in the area affected by drought.” In addition, they noted “evidence for widespread and unusual drying in European regions over the last few decades [as suggested by the work of Briffa *et al.* (1994) and Dai *et al.* (2004)] is not supported by the current work,” in that “values for the total percentage area subject to extreme moisture conditions in the years 1996–99 returned to normal levels at ~2% from a maximum of nearly 10% in 1990.” The four researchers noted “the absence of a trend toward summer desiccation has recently also been observed in soil moisture records in the Ukraine (Robock *et al.*, 2005) and supports conclusions in the current study.”

Pfister *et al.* (2006) identified extremely low water stages in the Upper Rhine River Basin via hydrological measurements made since 1808 at Basel,

Switzerland, while “for the period prior to 1808, rocks emerging in rivers and lakes in the case of low water were used along with narrative evidence for assessing extreme events.” This work revealed “29 severe winter droughts are documented since 1540,” and these events “occurred after a succession of four months with below-average precipitation” associated with “persistent anticyclones centered over Western Europe.” The scientists found “severe winter droughts were relatively rare in the 20th century compared to the former period, which is due to increased winter temperature and precipitation.” They noted “extended droughts in the winter half-year in Central Europe were more frequent, more persistent and more severe during the Little Ice Age than in the preceding ‘Medieval Warm Period’ and the subsequent ‘warm 20th century’ (Pfister, 2005).”

Renard *et al.* (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high- and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations with a minimum record length of 40 years. These analyses revealed “at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive.” At the smaller scale of hydroclimatic regions, they also found no significant results for most regions, although “consistent changes were detected in three geographical areas.”

Although small geographical areas often display trends in hydrological regimes of one extreme or the other (high- or low-flow), when scaling up to larger regions such as countries, there is typically less consistent change in extreme behavior. Renard *et al.* concluded “when considered at the global scale,” the impact of climate change on hydrological regimes “is still an open question, as illustrated by the lack of a clear signal emerging from large-scale studies (Knudzewicz *et al.*, 2005; Svensson *et al.*, 2005).”

Buntgen *et al.* (2011) “introduce and analyze 11,873 annually resolved and absolutely dated ring-width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period,” and which “allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations.” The nine researchers found “a fairly uniform distribution of hydroclimatic extremes

throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming.” Such findings, Buntgen *et al.* stated, “may question the common belief that frequency and severity of such events closely relates to climate mean states.”

References

- Briffa, K.R., Jones, P.D., and Hulme, M. 1994. Summer moisture variability across Europe, 1892-1991: An analysis based on the Palmer Drought Severity Index. *International Journal of Climatology* **14**: 475–506.
- Buntgen, U., Brazdil, R., Heussner, K.-U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chroma, K., and Tegel, W. 2011. Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium. *Quaternary Science Reviews* **30**: 3947–3959.
- Dai, A., Trenberth, K.E., and Qian, T. 2004. A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* **5**: 1117–1130.
- Ducic, V. 2005. Reconstruction of the Danube discharge on hydrological station Orsova in pre-instrumental period: possible causes of fluctuations. *Edition Physical Geography of Serbia* **2**: 79–100.
- Hisdal, H., Stahl, K., Tallaksen, L.M., and Demuth, S. 2001. Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology* **21**: 317–333.
- Jylha, K., Tuomenvirta, H., and Ruosteenoja, K. 2004. Climate change projections in Finland during the 21st century. *Boreal Environmental Research* **9**: 127–152.
- Knudzewicz, Z.W., Graczyk, D., Maurer, T., Pinskiar, I., Radziejewski, M., Svensson, C., and Szwed, M. 2005. Trend detection in river flow series: 1. Annual maximum flow. *Hydrological Sciences Journal* **50**: 797–810.
- Korhonen, J. and Kuusisto, E. 2010. Long-term changes in the discharge regime in Finland. *Hydrology Research* **41**: 253–268.
- Linderholm, H.W. and Chen, D. 2005. Central Scandinavian winter precipitation variability during the past five centuries reconstructed from *Pinus sylvestris* tree rings. *Boreas* **34**: 44–52.
- Linderholm, H.W. and Molin, T. 2005. Early nineteenth century drought in east central Sweden inferred from dendrochronological and historical archives. *Climate Research* **29**: 63–72.
- Pfister, C. 2005. Weeping in the snow. The second period of Little Ice Age-type impacts, 1570–1630. In: Behringer, W., Lehmann, H. and Pfister, C. (Eds.) *Kulturelle Konsequenzen der “Kleinen Eiszeit,”* Vandenhoeck, Gottingen, Germany, pp. 31–86.
- Pfister, C., Weingartner, R., and Luterbacher, J. 2006. Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. *Journal des Sciences Hydrologiques* **51**: 966–985.
- Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Sauquet, E., Prudhomme, C., Parey, S., Paquet, E., Neppel, L., and Gailhard, J. 2008. Regional methods for trend detection: Assessing field significance and regional consistency. *Water Resources Research* **44**: 10.1029/2007WR006268.
- Robock, A., Mu, M., Vinnikov, K., Trofimova, I.V., and Adamenko, T.I. 2005. Forty-five years of observed soil moisture in the Ukraine: No summer desiccation (yet). *Geophysical Research Letters* **32**: 10.1029/2004GL021914.
- Svensson, C., Kundzewicz, Z.W., and Maurer, T. 2005. Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrological Sciences Journal* **50**: 811–824.
- van der Schrier, G., Briffa, K.R., Jones, P.D., and Osborn, T.J. 2006. Summer moisture variability across Europe. *Journal of Climate* **19**: 2818–2834.
- Wells, N., Goddard, S., and Hayes, M.J. 2004. A self-calibrating Palmer Drought Severity Index. *Journal of Climate* **17**: 2335–2351.
- Wilson, R.J., Luckman, B.H., and Esper, J. 2005. A 500 year dendroclimatic reconstruction of spring-summer precipitation from the lower Bavarian Forest region, Germany. *International Journal of Climatology* **25**: 611–630.

7.4.4 North America

7.4.4.1 Canada

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Canada.

Gan (1998) performed several statistical tests on datasets pertaining to temperature, precipitation, spring snowmelt dates, streamflow, potential and actual evapotranspiration, and the duration, magnitude, and severity of drought throughout the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The results suggested the prairies have

become somewhat warmer and drier over the past four to five decades, although there are regional exceptions to this. After weighing the pertinent facts, Gan reported “there is no solid evidence to conclude that climatic warming, if it occurred, has caused the Prairie drought to become more severe.” Gan further noted “the evidence is insufficient to conclude that warmer climate will lead to more severe droughts in the Prairies.”

Quiring and Papakyriakou (2005) used an agricultural drought index (Palmer’s Z-index) to characterize the frequency, severity, and spatial extent of June–July moisture anomalies for 43 crop districts from the agricultural region of the Canadian prairies during 1920–1999. They found the single most severe June–July drought on the Canadian prairies occurred in 1961, and the next most severe droughts, in descending order of severity, occurred in 1988, 1936, 1929, and 1937, showing little net overall trend. The scientists did, however, report an upward trend in mean June–July moisture conditions. In addition, they noted “reconstructed July moisture conditions for the Canadian prairies demonstrate that droughts during the 18th and 19th centuries were more persistent than those of the 20th century (Sauchyn and Skinner, 2001).”

St. George and Nielsen (2002) used “a ringwidth chronology developed from living, historical and subfossil bur oak in the Red River basin to reconstruct annual precipitation in southern Manitoba since AD 1409.” According to the authors, “prior to the 20th century, southern Manitoba’s climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement.” The twentieth century warming appears to have induced more stable climatic conditions there, with fewer hydrologic extremes (floods and droughts) than was typical of Little Ice Age conditions. The authors concluded “climatic case studies in regional drought and flood planning based exclusively on experience during the 20th century may dramatically underestimate true worst-case scenarios.” They further indicated “multidecadal fluctuations in regional hydroclimate have been remarkably coherent across the northeastern Great Plains during the last 600 years,” and “individual dry years in the Red River basin were usually associated with larger scale drought across much of the North American interior,” which suggests their results for the Red River basin also likely apply to the entire larger region.

Campbell (2002) analyzed the grain sizes of

sediment cores obtained from Pine Lake, Alberta, Canada to derive a non-vegetation-based high-resolution record of climate variability over the past 4,000 years. Throughout this record, periods of both increasing and decreasing moisture availability, as determined from grain size, were evident at decadal, centennial, and millennial time scales, as also was found by Laird *et al.* (2003) in a study of diatom assemblages in sediment cores taken from three additional Canadian lakes. Over the most recent 150 years, the grain size of the Pine Lake study generally remained above the 4,000-year average, indicative of relatively stable and less droughty conditions than the mean of the past four millennia.

Carcaillet *et al.* (2001) developed high-resolution charcoal histories from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada, after which they determined whether vegetation change or climate change was the primary determinant of the fire frequency variation they observed, comparing their fire history with hydroclimatic reconstructions derived from $\delta^{18}\text{O}$ and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago when it was significantly warmer than it is today, they found “fire intervals were double those in the last 2000 years,” meaning fires were only half as frequent throughout the earlier warmer period as they were during the subsequent cooler era. They also determined “vegetation does not control the long-term fire regime in the boreal forest.” Instead, they found “climate appears to be the main process triggering fire.” In addition, they reported “dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al.*, 1990; Larsen, 1997; Weir *et al.*, 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al.*, 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993).”

Girardin *et al.* (2004) developed a 380-year reconstruction of the Canadian Drought Code (CDC), a daily numerical rating of the average moisture content of deep soil organic layers in boreal conifer stands used to monitor forest fire danger, for the month of July based on 16 well-replicated tree-ring chronologies from the Abitibi Plains of eastern Canada just below James Bay. Cross-continuous wavelet transformation analyses of these data

Observations: Extreme Weather

“indicated coherency in the 8–16 and 17–32-year per cycle oscillation bands between the CDC reconstruction and the Pacific Decadal Oscillation prior to 1850,” whereas “following 1850, the coherency shifted toward the North Atlantic Oscillation.”

These results led them to suggest “the end of [the] ‘Little Ice Age’ over the Abitibi Plains sector corresponded to a decrease in the North Pacific decadal forcing around the 1850s,” and “this event could have been followed by an inhibition of the Arctic air outflow and an incursion of more humid air masses from the subtropical Atlantic climate sector,” which may have helped reduce fire frequency and drought severity. They noted several other paleoclimate and ecological studies have suggested “climate in eastern Canada started to change with the end of the ‘Little Ice Age’ (~1850),” citing the works of Tardif and Bergeron (1997, 1999), Bergeron (1998, 2000), and Bergeron *et al.* (2001). Girardin *et al.* further noted Bergeron and Archambault (1993) and Hofgaard *et al.* (1999) have “speculated that the poleward retreat of the Arctic air mass starting at the end of the ‘Little Ice Age’ contributed to the incursion of moister air masses in eastern Canada.”

Wolfe *et al.* (2005) conducted a multiproxy hydroecological analysis of Spruce Island Lake in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta. Their research revealed hydroecological conditions in that region varied substantially during the past 300 years, especially in terms of multidecadal dry and wet periods. Specifically, they found recent drying in the region was not the product of Peace River flow regulation that began in 1968, but rather the product of an extended drying period that was initiated in the early to mid-1900s. They also found the multiproxy hydroecological variables they analyzed were well-correlated with other reconstructed records of natural climate variability and hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with the earlier portion of the record actually depicting “markedly wetter and drier conditions compared to recent decades.”

Zhang and Hebda (2005) conducted dendroclimatological analyses of 121 well-preserved sub-fossil logs discovered at the bottom of Heal Lake near the city of Victoria on Canada’s Vancouver Island, plus 29 Douglas-fir trees growing nearby, allowing them to develop an ~4,000-year chronology exhibiting sensitivity to spring precipitation. They found

“the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period.” As an example, they noted spring droughts represented by ring-width departures exceeding two standard deviations below the mean in at least five consecutive years occurred in the late AD 1840s and mid-1460s, as well as the mid-1860s BC, and were more severe than any drought of the twentieth century. They also found the most persistent drought occurred during the 120-year period between approximately AD 1440 and 1560. Other severe droughts of multidecadal duration occurred in the mid AD 760s–800s, the 540s–560s, the 150s–late-190s, and around 800 BC.

Wavelet analyses of the tree-ring chronology also revealed a host of natural oscillations on timescales of years to centuries, demonstrating the twentieth century was in no way unusual in this regard, as there were many times throughout the prior 4,000 years when it was both wetter and drier than it was during the last century of the past millennium.

Bonsal and Regier (2007) compared the spatial extent and severity of the 2001–2002 Canadian Prairie drought to previous droughts in this region based on data obtained from 21 reporting stations in southern Alberta, Saskatchewan, and Manitoba. They did this for the 1915–2002 period of reasonably extensive instrumental records, using two different drought indicators: the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) at several temporal scales. The two researchers determined “over the agricultural region of the Prairies, 2001 and 2002 generally ranked high in terms of spatial extent and severity of drought,” and “at some stations the 2001/2002 drought was the most severe one on record.” However, they stated “the SPI and PDSI as drought indicators revealed that the worst and most prolonged Prairie-wide droughts during the instrumental record (1915–2002) ... occurred in the early part of the 20th century (1915 through the 1930s).”

Laird and Cumming (2009) developed a history of changes in the level of Lake 259 (Rawson Lake, 49°40'N, 93°44'W) within the Experimental Lakes Area of northwestern Ontario, Canada, based on a suite of near-shore gravity cores they analyzed for diatom species identity and concentration as well as organic matter content. They found “a distinct decline in lake level of ~2.5 to 3.0 m from ~800 to 1130 AD.” This interval “corresponds to an epic drought recorded in many regions of North America from ~800 to 1400 AD,” which “is often referred to as the

Medieval Climatic Anomaly or the Medieval Warm Period, and encompasses ‘The Great Drought’ of the thirteenth century (Woodhouse and Overpeck, 1998; Woodhouse, 2004; Herweijer *et al.* 2007).”

The authors also noted the Canadian prairies are currently “experiencing reductions in surface-water availability due to climate warming and human withdrawals (Schindler and Donahue, 2006),” and “many regions in the western U.S. have experienced water supply deficits in reservoir storage with the recent multi-year drought (Cook *et al.*, 2007).” They reported “these severe multi-year drought conditions pale in comparison to the many widespread megadroughts that persisted for decades and sometimes centuries in many parts of North America over the last millennium (Woodhouse, 2004).”

Wolfe *et al.* (2011) noted the level of Canada’s Lake Athabasca—North America’s ninth-largest lake, located in the northwest corner of Saskatchewan and the northeast corner of Alberta between 58° and 60° N—“is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains (Wolfe *et al.*, 2008; Johnston *et al.*, 2010; Sinnatamby *et al.*, 2010)” and “paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks (Wolfe *et al.*, 2008).” In addition, they reported “the highest levels of the last 1000 years occurred c. 1600–1900 CE [=AD] during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies,” and at the other end of the spectrum they reported the “lowest levels existed at c. 970–1080 CE at a time of low glacier volume,” near the midpoint of the global Medieval Warm Period.

In their newest study of the subject, the four Canadian researchers expanded the timespan of the lake-level history to the past 5,200 years, based on new analyses of sediment cores they collected in July 2004 from North Pond (a lagoon on Bustard Island located at the western end of Lake Athabasca). They discovered “modern society in western Canada developed during a rare interval of relatively abundant freshwater supply—now a rapidly diminishing by-product of the LIA glacier expansion,

which is in agreement with late 20th century decline in Athabasca River discharge identified in hydro-metric records (Burn *et al.*, 2004; Schindler and Donahue, 2006)” (see Figure 7.4.4.1.1). Their data suggested “the transition from water abundance to scarcity can occur within a human lifespan,” which, as they caution, “is a very short amount of time for societies to adapt.”

The data depicted in Figure 7.4.4.1.1 also suggest the peak warmth of the Medieval Warm Period—which was unrelated to any change in the atmosphere’s CO₂ content—was likely significantly greater than the peak warmth to date during the Current Warm Period. The rapidly declining water level during the last couple of decades—when Earth’s temperature was near its modern peak but exhibited

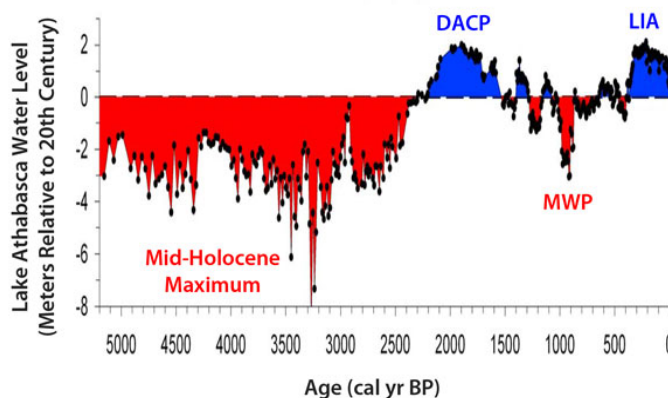


Figure 7.4.4.1.1. The Reconstructed water level history of Lake Athabasca. Adapted from Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.

very little trend—suggests lake level could continue its rapid downward course if planetary temperatures merely maintain their current values. Therefore, Wolfe *et al.* conclude, “as consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory.”

Sauchyn *et al.* (2011) observed “a growing demand for the surface water resources of the Canadian Prairie Provinces has resulted in increasing vulnerability to hydrological drought,” citing the studies of Schindler and Donahue (2006) and Wheaton *et al.* (2008). They further noted “a shift in

Observations: Extreme Weather

the amount and timing of streamflow represents the most serious risk from recent and projected climate warming in western Canada (Sauchyn *et al.*, 2010)” and “the Saskatchewan River Basin is among Canada’s most vulnerable watersheds, in terms of projected climate changes and impacts, and the sensitivity of natural systems and economic activities to Canada’s most variable hydroclimate.” It is, of course, important to know the characteristics of past streamflow variability in order to better prepare for future droughts and to determine whether extreme droughts that may occur in the future might be due to CO₂-induced global warming or are within the range of natural variability experienced in the past, when the air’s CO₂ concentration was both much lower and less variable than it is currently. Is a mere century of real-world data sufficient for these purposes?

In a study designed to explore this question by determining whether streamflow variability recorded by the streamflow gauge at Edmonton, Alberta (Canada) during the past century (since 1912) is representative of the range of variability experienced there during the past millennium, Sauchyn *et al.* developed a 945-year reconstruction of the annual flow of the Northern Saskatchewan River based on tree rings collected from seven sites within the runoff-generating upper basin of the river (Figure 7.4.4.1.2).

The Edmonton stream-gauge record clearly does not “represent the full extent of interannual to

multidecadal variability in the tree-ring data,” for as noted by Sauchyn *et al.* “there are periods of low flow in the pre-instrumental record that are longer and more severe than those recorded by the gauge” and which “pre-date Euro-Canadian settlement of the region.” Two of these extreme events were droughts of approximately 30 years’ duration, one in the early 1700s and another during the mid-1100s. One of the two most prominent megadroughts lasted for most of the fourteenth century, while the other occurred in the latter part of the fifteenth century.

Sauchyn *et al.* observe “there is less certainty and stationarity in western [Canadian] water supplies than implied by the instrumental record,” which is “the conventional basis for water resource management and planning” of the region. Their streamflow reconstruction provides an improved basis for determining the uniqueness of whatever future droughts might occur throughout the region. Their work also makes it more difficult to claim such droughts were caused by anthropogenic CO₂ emissions, since there was far less CO₂ in Earth’s atmosphere prior to the 1912 start date of the region’s prior streamflow history, when several droughts far more serious than those of the past century occurred.

Laird *et al.* (2012) wrote “future extreme droughts, similar to or more extreme than the ‘dust-bowl’ 1930s, could be the most pressing problem of global warming,” citing Romm (2011) and noting, for comparison, “droughts of unusually long duration” or megadroughts that occurred during the Medieval Climate Anomaly (MCA) “lasted for several decades to centuries thus dwarfing modern-day droughts,” as reported by Seager *et al.* (2007) and Cook *et al.* (2010).

Observing “one of the predictions of increasing temperatures is decreased lake levels and river flows (Schindler and Lee, 2010),” the eight researchers stated “analysis of longer-term records of past water levels can provide a context for informing water managers on the inherent natural variability of lake levels and their sensitivity to climate change.” They described a pertinent study they conducted on six lakes spread across a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada, where the land-based pollen data of Viau and Gajewski (2009) suggest the presence of warmer temperatures during the MCA.

The diatom-inferred decadal-scale two-millennia-long drought records, which Laird *et*

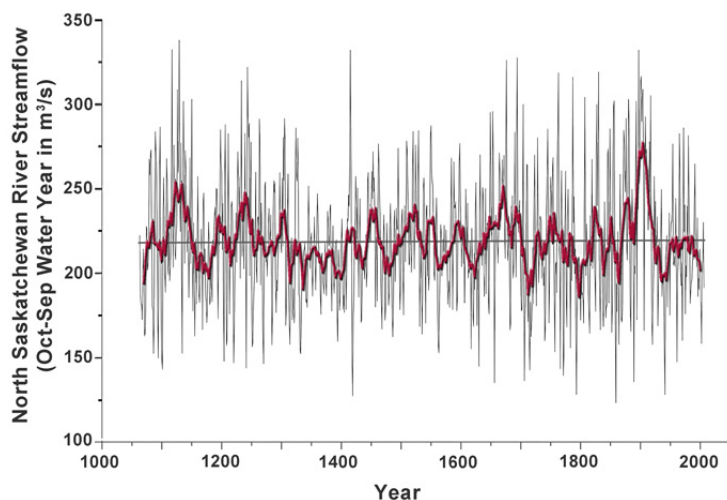


Figure 7.4.4.1.2. North Saskatchewan River reconstructed water year (October to September) flow for the period 1063–2006. Adapted from Sauchyn, D., Vanstone, J., and Perez-Valdivia, C. 2011. Modes and forcing of hydroclimatic variability in the upper North Saskatchewan River Basin since 1063. *Canadian Water Resources Journal* 36: 205–218.

al. developed for the six lakes they studied, revealed what they call “periods of synchronous change” had occurred across the six lakes throughout “a period of prolonged aridity during the MCA (c. 900–1400 CE).” They reported this “general synchrony across sites suggests an extrinsic climate forcing (Williams *et al.*, 2011),” with the MCA being part of a set of what they call “inherent natural fluctuations.”

Laird *et al.* also noted “a widespread external forcing must be large enough for regional patterns to emerge.” In the Nebraska Sandhills, they reported, “an analysis of five topographically closed lakes indicated relative coherency over the last 4,000 years, particularly during the MCA with all lakes indicating lake-level decline (Schmieder *et al.*, 2011).” In addition, “in Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al.*, 2008), high eolian deposition occurred from ~1280 to 1410 CE in Elk Lake (Dean, 1997) and $\delta^{18}\text{O}$ from calcite indicated an arid period from ~1100 to 1400 CE in Steel Lake (Tian *et al.*, 2006),” while “in Manitoba, the cellulose $\delta^{18}\text{O}$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 CE, and a less-severe dry period from 1320 to 1340 CE (Buhay *et al.*, 2009).” Relatively warm conditions during the MCA, they added, “have been inferred from pollen records in the central boreal region of Canada and in Wisconsin,” citing Viau and Gajewski (2009), Viau *et al.* (2012), and Wahl *et al.* (2012).

These findings have important implications. Most germane to climatology is this: If future extreme droughts, such as those that occurred during the MCA, could indeed be the “most pressing problem” of projected future global warming, as many contend, then it logically follows the Medieval Warm Period must have been far more extreme in terms of high temperature values and their duration than anything yet experienced during the Current Warm Period. That observation is strong evidence that warming considerably in excess of what has been experienced to date in the CWP can occur without any help from rising atmospheric CO_2 concentrations, which were more than 100 ppm less during the Medieval Warm Period than they are today. The great warmth of the MWP is demonstrated by the quantitative and qualitative findings of a host of scientists who have studied the Medieval and Current Warm Periods (see Chapter 4 of this report), all of which further suggests the development of the planet’s Current Warm Period may be due to something entirely unrelated to anthropogenic CO_2 emissions.

References

- Bergeron, Y. 1991. The influence of island and mainland lakeshore landscape on boreal forest fire regime. *Ecology* **72**: 1980–1992.
- Bergeron, Y. 1998. Les conséquences des changements climatiques sur la fréquence des feux et la composition forestière au sud-ouest de la forêt boréale québécoise. *Géographie Physique et Quaternaire* **52**: 167–173.
- Bergeron, Y. 2000. Species and stand dynamics in the mixed woods of Quebec’s boreal forest. *Ecology* **81**: 1500–1516.
- Bergeron, Y. and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the ‘Little Ice Age’. *The Holocene* **3**: 255–259.
- Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research* **31**: 384–391.
- Bonsal, B. and Regier, M. 2007. Historical comparison of the 2001/2002 drought in the Canadian Prairies. *Climate Research* **33**: 229–242.
- Buhay, W.M., Simpson, S., Thorleifson, H., Lewis, M., King, J., Telka, A., Wilkinson, P., Babb, J., Timsic, S., and Bailey, D. 2009. A 1000 year record of dry conditions in the eastern Canadian prairies reconstructed from oxygen and carbon isotope measurements on Lake Winnipeg sediment organics. *Journal of Quaternary Science* **24**: 426–436.
- Burn, D.H., Abdul Aziz, O.I., and Pictroniro, A. 2004. A comparison of trends in hydrological variables for two watersheds in the Mackenzie River Basin. *Canadian Water Resources Journal* **29**: 283–298.
- Campbell, C. 2002. Late Holocene lake sedimentology and climate change in southern Alberta, Canada. *Quaternary Research* **49**: 96–101.
- Carcaillet, C., Bergeron, Y., Richard, P.J.H., Frechette, B., Gauthier, S., and Prairie, Y.T. 2001. Change of fire frequency in eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *Journal of Ecology* **89**: 930–946.
- Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American drought: reconstructions, causes, and consequences. *Earth Science Reviews* **81**: 93–134.
- Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2010. Mega-droughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* **25**: 48–61.

Observations: Extreme Weather

- Cwynar, L.C. 1977. Recent history of fire of Barrow Township, Algonquin Park. *Canadian Journal of Botany* **55**: 10–21.
- Dean, W.E. 1997. Rates, timing and cyclicity of Holocene eolian activity in north-central US: evidence from varved lake sediments. *Geology* **25**: 331–334.
- Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. *Canadian Journal of Botany* **61**: 2459–2471.
- Gan, T.Y. 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. *Water Resources Research* **34**: 3009–3015.
- Girardin, M.-P., Tardif, J., Flannigan, M.D., and Bergeron, Y. 2004. Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. *Climate Dynamics* **23**: 99–115.
- Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.
- Hofgaard, A., Tardif, J., and Bergeron, Y. 1999. Dendroclimatic response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest. *Canadian Journal of Forest Research* **29**: 1333–1346.
- Johnson, E.A., Fryer, G.I., and Heathcott, J.M. 1990. The influence of Man and climate on frequency of fire in the interior wet belt forest, British Columbia. *Journal of Ecology* **78**: 403–412.
- Johnston, J.W., Koster, D., Wolfe, B.B., Hall, R.I., Edwards, T.W.D., Endres, A.L., Martin, M.E., Wiklund, J.A., and Light, C. 2010. Quantifying Lake Athabasca (Canada) water level during the Little Ice Age highstand from paleolimnological and geophysical analyses of a transgressive barrier-beach complex. *The Holocene* **20**: 801–811.
- Laird, K.R. and Cumming, B.F. 2009. Diatom-inferred lake level from near-shore cores in a drainage lake from the Experimental Lakes Area, northwestern Ontario, Canada. *Journal of Paleolimnology* **42**: 65–80.
- Laird, K.R., Cumming, B.F., Wunsam, S., Rusak, J.A., Oglesby, R.J., Fritz, S.C., and Leavitt, P.R. 2003. Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proceedings of the National Academy of Sciences USA* **100**: 2483–2488.
- Laird, K.R., Haig, H.A., Ma, S., Kingsbury, M.V., Brown, T.A., Lewis, C.F.M., Oglesby, R.J., and Cumming, B.F. 2012. Expanded spatial extent of the Medieval Climate Anomaly revealed in lake-sediment records across the boreal region in northwest Ontario. *Global Change Biology* **18**: 2869–2881.
- Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *Journal of Biogeography* **24**: 663–673.
- Quiring, S.M. and Papakyriakou, T.N. 2005. Characterizing the spatial and temporal variability of June–July moisture conditions in the Canadian prairies. *International Journal of Climatology* **25**: 117–138.
- Romm, J. 2011. The next dust bowl. *Nature* **478**: 450–451.
- Sauchyn, D.J. and Skinner, W.R. 2001. A proxy record of drought severity for the southwestern Canadian plains. *Canadian Water Resources Journal* **26**: 253–272.
- Sauchyn, D., Vanstone, J., and Perez-Valdivia, C. 2011. Modes and forcing of hydroclimatic variability in the upper North Saskatchewan River Basin since 1063. *Canadian Water Resources Journal* **36**: 205–218.
- Schindler, D.W. and Donahue, W.F. 2006. An impending water crisis in Canada’s western prairie provinces. *Proceedings of the National Academy of Sciences, USA* **103**: 7210–7216.
- Schindler, D.W. and Lee, P.G. 2010. Comprehensive conservation planning to protect biodiversity and ecosystem services in Canadian boreal regions under a warming climate and increasing exploitation. *Biological Conservation* **143**: 1571–1586.
- Schmieder, J., Fritz, S.C., Swinehart, J.B., Shinneman, A., Wolfe, A.P., Miller, G., Daniels, N., Jacobs, K., and Grimm, E.C. 2011. A regional-scale climate reconstruction of the last 4000 years from lakes in the Nebraska sand hills, USA. *Quaternary Science Reviews* **30**: 1797–1812.
- Seager, R., Graham, N., Herweijer, C., Gorodn, A.L., Kushnir, Y., and Cook, E. 2007. Blueprints for medieval hydroclimate. *Quaternary Science Reviews* **26**: 2322–2336.
- Sinnatamby, R.N., Yi, Y., Sokal, M.A., Clogg-Wright, K.P., Asada, T., Vardy, S.H., Karst-Riddoch, T.L., Last, W.M., Johnston, J.W., Hall, R.I., Wolfe, B.B., and Edwards, T.W.D. 2010. Historical and paleolimnological evidence for expansion of Lake Athabasca (Canada) during the Little Ice Age. *Journal of Paleolimnology* **43**: 705–717.
- St. George, S. and Nielsen, E. 2002. Hydroclimatic change in southern Manitoba since A.D. 1409 inferred from tree rings. *Quaternary Research* **58**: 103–111.
- St. Jacques, J.M., Cumming, B.F., and Smol, J.P. 2008. A 900-year pollen-inferred temperature and effective moisture record from varved Lake Mina, west-central Minnesota, USA. *Quaternary Science Reviews* **27**: 781–796.
- Tardif, J. and Bergeron, Y. 1997. Ice-flood history

reconstructed with tree-rings from the southern boreal forest limit, western Quebec. *The Holocene* **7**: 291–300.

Tardif, J. and Bergeron, Y. 1999. Population dynamics of *Fraxinus nigra* in response to flood-level variations, in northwestern Quebec. *Ecological Monographs* **69**: 107–125.

Tian, J., Nelson, D.M., and Hu, F.S. 2006. Possible linkages of late-Holocene drought in the North American midcontinent to Pacific Decadal Oscillation and solar activity. *Geophysical Research Letters* **33**: 10.1029/2006GL028169.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**: 220–227.

Viau, A.E. and Gajewski, K. 2009. Reconstructing millennial-scale, regional paleoclimates of boreal Canada during the Holocene. *Journal of Climate* **22**: 316–330.

Viau, A.E., Ladd, M., and Gajewski, K. 2012. The climate of North America during the past 2000 years reconstructed from pollen data. *Global and Planetary Change* **84–85**: 75–83.

Wahl, E.R., Diaz, H.F., and Ohlwein, C. 2012. A pollen-based reconstruction of summer temperature in central North America and implications for circulation patterns during medieval times. *Global and Planetary Change* **84–85**: 66–74.

Weir, J.M.H., Johnson, E.A., and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecological Applications* **10**: 1162–1177.

Wheaton, E., Kulshreshtha, S., Wittrock, V., and Koshida, G. 2008. Dry times: hard lessons from the Canadian drought of 2001 and 2002. *Canadian Geographer* **52**: 241–262.

Williams, J.W., Blois, J.L., and Shuman, B.N. 2011. Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *Journal of Ecology* **99**: 664–677.

Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.

Wolfe, B.B., Hall, R.I., Edwards, T.W.D., Jarvis, S.R., Sinnatamby, R.N., Yi, Y., and Johnston, J.W. 2008. Climate-driven shifts in quantity and seasonality of river discharge over the past 1000 years from the hydrographic apex of North America. *Geophysical Research Letters* **35**: 10.1029/2008GL036125.

Wolfe, B.B., Karst-Riddoch, T.L., Vardy, S.R., Falcone, M.D., Hall, R.I., and Edwards, T.W.D. 2005. Impacts of climate and river flooding on the hydro-ecology of a floodplain basin, Peace-Athabasca Delta, Canada since A.D. 1700. *Quaternary Research* **64**: 147–162.

Woodhouse, C.A. 2004. A paleo-perspective on hydroclimatic variability in the western United States. *Aquatic Science* **66**: 346–356.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

Zhang, Q.-B. and Hebda, R.J. 2005. Abrupt climate change and variability in the past four millennia of the southern Vancouver Island, Canada. *Geophysical Research Letters* **32** L16708, doi:10.1029/2005GL022913.

7.4.4.2 Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Mexico.

Stahle *et al.* (2000) developed a long-term history of drought over much of North America from reconstructions of the Palmer Drought Severity Index, based on analyses of many lengthy tree-ring records. This history revealed the occurrence of a sixteenth century drought in Mexico that persisted from the 1540s to the 1580s. The authors observed “the ‘megadrought’ of the 16th century far exceeded any drought of the 20th century.”

Diaz *et al.* (2002) constructed a history of winter-spring (November–April) precipitation—which accounts for one-third of the yearly total—for the Mexican state of Chihuahua for the period 1647–1992, based on earlywood width chronologies of more than 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua’s northeast border. They noted “three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century.” Although this observation tends to make the twentieth century look highly anomalous in this regard, it is not; two of those three worst drought years occurred during a period of average to slightly above-average precipitation.

Diaz *et al.* also noted “the longest drought

indicated by the smoothed reconstruction lasted 17 years (1948–1964),” again indicative of abnormally dry conditions during the twentieth century. However, for several of the 17 years of that below-normal-precipitation interval, precipitation values were only slightly below normal. Four very similar dry periods were interspersed throughout the preceding two and a half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s.

In the twentieth century, there also was a long period of high winter-spring precipitation from 1905 to 1932, and following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record. With respect to the entire 346 years, Diaz *et al.* found no long-term trend in the data, nor was there evidence of any sustained departure from that trend during the twentieth century, indicating neither twentieth century anthropogenic CO₂ emissions nor twentieth century warming significantly affected rainfall in the Mexican state of Chihuahua.

Cleaveland *et al.* (2003) constructed a winter-spring (November–March) precipitation history for the period 1386–1993 for Durango, Mexico based on earlywood width chronologies of Douglas-fir tree rings collected at two sites in the Sierra Madre Occidental. They reported this record “shows droughts of greater magnitude and longer duration than the worst historical drought that occurred in the 1950s and 1960s.” These earlier dramatic droughts included the long dry spell of the 1850s–1860s and what they call the megadrought of the mid- to late-sixteenth century. Their work demonstrates the worst droughts of the past 600 years did not occur during the period of greatest warmth. Instead, they occurred during the Little Ice Age, perhaps the coldest period of the current interglacial.

Hodell *et al.* (2005b) analyzed a 5.1-m sediment core they retrieved from Aguada X’caamal, a small sinkhole lake in northwest Yucatan, Mexico, finding an important hydrologic change occurred there during the fifteenth century AD. The change was documented by the appearance of *A. beccarii* in the sediment profile, a decline in the abundance of charophytes, and an increase in the $\delta^{18}\text{O}$ of gastropods and ostracods. In addition, they reported “the salinity and ^{18}O content of the lake water increased as a result of reduced precipitation and/or increased evaporation in the mid- to late 1500s.” These changes, as well as many others they cited, were “part of a larger pattern

of oceanic and atmospheric change associated with the Little Ice Age that included cooling throughout the subtropical gyre (Lund and Curry, 2004).” They wrote, the “climate became drier on the Yucatan Peninsula in the 15th century AD near the onset of the Little Ice Age,” as is also suggested by Maya and Aztec chronicles that “contain references to cold, drought and famine in the period AD 1441–1460.”

Hodell *et al.* (1995) provided evidence for a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800–1000), based on their analysis of a sediment core retrieved in 1993 from Lake Chichanacanab in the center of Mexico’s northern Yucatan Peninsula. Subsequently, based on two additional sediment cores retrieved from that location in 2000, Hodell *et al.* (2001) determined the massive drought likely occurred in two distinct phases (750–875 and 1000–1075). Reconstructing the climatic history of the region over the past 2,600 years and applying spectral analysis to the data also revealed a significant recurrent drought periodicity of 208 years that matched well with a cosmic ray-produced ^{14}C record preserved in tree rings. This periodicity is believed to reflect variations in solar activity; because of the good correspondence between the two datasets, Hodell *et al.* concluded “a significant component of century-scale variability in Yucatan droughts is explained by solar forcing.”

Hodell *et al.* (2005a) returned to Lake Chichanacanab in March 2004 and retrieved a number of additional sediment cores in some of the deeper parts of the lake. The scientists took multiple cores from the lake’s deepest location, from which they obtained depth profiles of bulk density by means of gamma-ray attenuation as well as profiles of reflected red, green, and blue light via a digital color line-scan camera. They observed, “the data reveal in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization.” They reported “the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions,” and it “included an early phase (ca 770–870) and late phase (ca 920–1100).” They found “the bipartite drought history inferred from Chichanacanab is supported by oxygen isotope records from nearby Punta Laguna” and “the general pattern is also consistent with findings from the Cariaco Basin off northern Venezuela (Haug *et al.*, 2003), suggesting that the Terminal Classic Drought was a widespread phenomenon and not

limited to north-central Yucatan.”

Concurrent with the study of Hodell *et al.* (2005a), Almeida-Lenero *et al.* (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala and nearby Lake Quila in the central Mexican highlands approximately 65 km southwest of Mexico City. The scientists determined it was generally more humid than at present in the central Mexican highlands during the mid-Holocene. Thereafter, however, there was a gradual drying of the climate. Their data from Lake Zempoala indicated “the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene.” They further noted this interval of 200 years “coincides with the collapse of the Maya civilization.” They reported their data from Lake Quila were “indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP.” In addition, they noted “climatic aridity during this time was also noted by Metcalfe *et al.* (1991) for the Lerma Basin [central Mexico]” and “dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982).” The “dry conditions were also reported for [Mexico’s] Zacapu Basin (Metcalfe, 1995) and for [Mexico’s] Yucatan Peninsula (Curtis *et al.*, 1996, 1998; Hodell *et al.*, 1995, 2001).”

Therrell *et al.* (2006) “developed a continuous, exactly dated, tree-ring reconstruction of maize yield variability” over the period 1474 to 2001 in an effort to provide “new insight into the history of climate and food availability in the heartland of the Mesoamerican cultural province.” They relied on latewood-width data derived from “the second-most southerly native stand of Douglas-fir (*Pseudotsuga menziesii*) trees known in the Americas” and compared their reconstruction to “historical records of crop failure and famine in order to cross-validate the tree-ring and historical records.”

Therrell *et al.*’s plot of reconstructed drought-induced maize-yield anomalies exposed seven major decadal-scale yield shortfalls over the past 500 years, with a mean rate of occurrence of 1.5 per century over the 400-year period AD 1500–1900. In the twentieth century, there was only one such multiyear famine, and its magnitude paled in comparison to that of the average such event of the preceding four centuries.

Metcalfe and Davies (2007) synthesized the findings of a variety of paleoclimate studies based on analyses of the sediment records of several crater lakes and lakes formed by lava dams scattered across

the Trans Mexican Volcanic Belt of central Mexico with an absolute chronology provided by radiocarbon dates extending back to 1500 ¹⁴C yr BP. Noting the degree of coherence among the records “is remarkable,” Metcalf and Davis reported “dry conditions, probably the driest of the Holocene, are recorded over the period 1400 to 800 ¹⁴C yr BP (ca. AD 700–1200).” The authors reported the results were “consistent with results from the Yucatan Peninsula (Hodell *et al.*, 1995, 2005) ... and from the Cariaco basin (Haug *et al.*, 2003) and the Isthmus of Panama (Lachniet *et al.*, 2004).”

Dominguez-Vazquez and Islebe (2008) derived a 2,000-year history of regional drought for the Lacandon Forest Region in the state of Chiapas, southeastern Mexico. Based on radiocarbon dating and pollen analyses of a sediment core retrieved from the shore of Naja Lake (16°59'27.6"N, 91°35'29.6"W), the two authors reported “a marked increase in *Pinus* pollen, together with a reduction in lower montane rain forest taxa, [which they] interpreted as evidence for a strong, protracted drought from 1260 to 730 years BP,” which they characterized as “the most severe” while noting it “coincides with the Maya classic collapse.”

Escobar *et al.* (2010) examined sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula as a proxy measure for high-frequency climate variability. The five researchers found “relatively dry periods were persistently dry, whereas relatively wet periods were composed of wet and dry times.” They noted their findings “confirm the interpretations of Hodell *et al.* (1995, 2007) and Curtis *et al.* (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period.” They found “the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the last 3,000 years, but also a persistently dry period.” In further support of this interpretation, they note “the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability.”

Figuerola-Rangel *et al.* (2010) used fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35'32"N, 104°16'56"W) to construct a 1,300-year history of cloud forest vegetation dynamics in the Sierra de Manantlan Biosphere Reserve (SMBR, in west-central Mexico). The authors found “during intervals of aridity, cloud forest taxa tend to become

Observations: Extreme Weather

reduced,” whereas “during intervals of increased humidity, the cloud forest thrives.” They determined there was a major dry period from approximately AD 800 to 1200 in the SMBR and observed “results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region (B.L. Figueroa-Rangel, unpublished data); in central Mexico (Metcalf and Hales, 1994; Metcalfe, 1995; Arnould *et al.*, 1997; O’Hara and Metcalfe, 1997; Almeida-Lenero *et al.*, 2005; Ludlow-Wiechers *et al.*, 2005; Metcalfe *et al.*, 2007); lowlands of the Yucatan Peninsula (Hodell *et al.*, 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug *et al.*, 2003).” In addition, they reported “the causes associated to this phase of climate change have been attributed to solar activity (Hodell *et al.*, 2001; Haug *et al.*, 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe *et al.*, 2000; Hodell *et al.*, 2005a,b; Berrio *et al.*, 2006) and to ENSO variability (Metcalfe, 2006).”

Throughout much of Mexico, some of the driest conditions and worst droughts of the Late Holocene occurred prior to the late twentieth and early twenty-first centuries. These observations contradict assertions that global warming will cause drought conditions to worsen, especially considering the Mexican droughts of the twentieth century and early twenty-first century were much milder than many of that occurred during the much colder centuries of the Little Ice Age and the warmer Medieval Warm Period. The latter observation suggests that to attribute warmth as the cause of droughts means acknowledging the Medieval Warm Period extended beyond the North Atlantic and was significantly warmer than current and recent temperatures.

References

Almeida-Lenero, L., Hooghiemstra, H., Cleef, A.M., and Van Geel, B. 2005. Holocene climatic and environmental change from pollen records of Lakes Zempoala and Quila, central Mexican highlands. *Review of Palaeobotany and Palynology* **136**: 63–92.

Arnould, C., Metcalfe, S., and Petrequin, P. 1997. Holocene climatic change in the Zacapu Lake Basin, Michoacan: synthesis of results. *Quaternary International* **43/44**: 173–179.

Berrio, J.C., Hooghiemstra, H., van Geel, B., and Ludlow-Wiechers, B. 2006. Environmental history of the dry forest biome of Guerrero, Mexico, and human impact during the last c. 2700 years. *The Holocene* **16**: 63–80.

Cleaveland, M.K., Stahle, D.W., Therrell, M.D., Villanueva-Diaz, J., and Burns, B.T. 2003. Tree-ring reconstructed winter precipitation and tropical teleconnections in Durango, Mexico. *Climatic Change* **59**: 369–388.

Curtis, J., Brenner, M., Hodell, D., Balser, R., Islebe, G.A., and Hooghiemstra, H. 1998. A multi-proxy study of Holocene environmental change in the Maya Lowlands of Peten Guatemala. *Journal of Paleolimnology* **19**: 139–159.

Curtis, J., Hodell, D., and Brenner, M. 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. *Quaternary Research* **46**: 37–47.

Diaz, S.C., Therrell, M.D., Stahle, D.W., and Cleaveland, M.K. 2002. Chihuahua (Mexico) winter-spring precipitation reconstructed from tree-rings, 1647–1992. *Climate Research* **22**: 237–244.

Dominguez-Vazquez, G. and Islebe, G.A. 2008. Protracted drought during the late Holocene in the Lacandon rain forest, Mexico. *Vegetation History and Archaeobotany* **17**: 327–333.

Escobar, J., Curtis, J.H., Brenner, M., Hodell, D.A., and Holmes, J.A. 2010. Isotope measurements of single ostracod valves and gastropod shells for climate reconstruction: Evaluation of within-sample variability and determination of optimum sample size. *Journal of Paleolimnology* **43**: 921–938.

Figueroa-Rangel, B.L., Willis, K.J., and Olvera-Vargas, M. 2010. Cloud forest dynamics in the Mexican neotropics during the last 1300 years. *Global Change Biology* **16**: 1689–1704.

Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., and Aeschlimann, B. 2003. Climate and the collapse of the Maya civilization. *Science* **299**: 1731–1735.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2005a. Terminal classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). *Quaternary Science Reviews* **24**: 1413–1427.

Hodell, D.A., Brenner, M., and Curtis, J.H. 2007. Climate and cultural history of the Northeastern Yucatan Peninsula, Quintana Roo, Mexico. *Climatic Change* **83**: 215–240.

Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T. 2001. Solar forcing of drought frequency in the Maya lowlands. *Science* **292**: 1367–1369.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E. I.-C., Albornaz-Pat, A., and Guilderson, T.P. 2005b. Climate change on the Yucatan Peninsula during the Little Ice Age. *Quaternary Research* **63**: 109–121.

Climate Change Reconsidered II

Hodell, D.A., Curtis, J., and Brenner, M. 1995. Possible role of climate in the collapse of classic Maya civilization. *Nature* **375**: 391–394.

Lachniet, M.S., Burns, S.J., Piperno, D.R., Asmerom, Y., Polyak, V.J., Moy, C.M., and Christenson, K. 2004. A 1500-year El Niño/Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite. *Journal of Geophysical Research* **109**: 10.1029/2004JD004694.

Ludlow-Wiechers, B., Almeida-Lenero, L., and Islebe, G. 2005. Paleocological and climatic changes of the Upper Lerma Basin, Central Mexico during the Holocene. *Quaternary Research* **64**: 318–332.

Lund, D.C. and Curry, W.B. 2004. Late Holocene variability in Florida Current surface density: patterns and possible causes. *Paleoceanography* **19**: 10.1029/2004PA001008.

Metcalf, S.E. 1995. Holocene environmental change in the Zacapu Basin, Mexico: a diatom based record. *The Holocene* **5**: 196–208.

Metcalf, S.E. 2006. Late Quaternary environments of the northern deserts and central transvolcanic belt of Mexico. *Annals of the Missouri Botanical Garden* **93**: 258–273.

Metcalf, S.E. and Davies, S.J. 2007. Deciphering recent climate change in central Mexican lake records. *Climatic Change* **83**: 169–186.

Metcalf, S.E., Davies, S.J., Braisby, J.D., Leng, M.J., Newton, A.J., Terrett, N.L., and O'Hara, S.L. 2007. Long-term changes in the Patzcuaro Basin, central Mexico. *Palaeogeography, Palaeoclimatology, Palaeoecology* **247**: 272–295.

Metcalf, S.E. and Hales, P.E. 1994. Holocene diatoms from a Mexican crater lake—La Piscina Yuriria. In: *Proceedings of the 11th International Diatom Symposium, San Francisco, USA, 1990* **17**: 155–171. California Academy of Sciences, San Francisco, California, USA.

Metcalf, S.E., O'Hara, S.L., Caballero, M., and Davies, S.J. 2000. Records of Late Pleistocene-Holocene climatic change in Mexico—a review. *Quaternary Science Reviews* **19**: 699–721.

Metcalf, S.E., Street-Perrott, F.A., Perrott, R.A., and Harkness, D.D. 1991. Palaeolimnology of the Upper Lerma Basin, central Mexico: a record of climatic change and anthropogenic disturbance since 11,600 yr B.P. *Journal of Paleolimnology* **5**: 197–218.

O'Hara, S.L. and Metcalf, S.E. 1997. The climate of Mexico since the Aztec period. *Quaternary International* **43/44**: 25–31.

Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell,

M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and Luckman, B.H. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, Transactions, American Geophysical Union* **81**: 121, 125.

Therrell, M.D., Stahle, D.W., Villanueva Diaz, J., Cornejo Oviedo, E.H., and Cleaveland, M.K. 2006. Tree-ring reconstructed maize yield in central Mexico: 1474–2001. *Climatic Change* **74**: 493–504.

Watts, W.A. and Bradbury, J.P. 1982. Paleocological studies at Lake Patzcuaro on the West Central Mexican plateau and at Chalco in the Basin of Mexico. *Quaternary Research* **17**: 56–70.

7.4.4.3 United States

7.4.4.3.1 Central

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the central United States.

The United States' Northern Great Plains is an important agricultural region of North America, providing a significant source of grain both locally and internationally. It is susceptible to extreme droughts that tend to persist longer than in any other region of the country (Karl *et al.*, 1987; Soule, 1992), making it a good place to review the history of drought to determine whether the region is currently experiencing a manifestation of the model-based claim (Gore, 2006; Mann and Kump, 2008) that global warming will usher in a period of more frequent and intense drought.

Mauget (2004) looked for what he called “initial clues” to the commencement of the great drying of the U.S. heartland predicted to occur in response to CO₂-induced global warming by Manabe and Wetherald (1987), Rind *et al.* (1990), Rosenzweig and Hillel (1993), and Manabe *et al.* (2004), which Mauget reasoned would be apparent in the observational streamflow record of the region. He employed data obtained from the archives of the U.S. Geological Survey's Hydro-Climatic Data Network, 42 stations covering the central third of the United States stretching from the Canadian border on the north to the Gulf of Mexico on the south, with the densest coverage existing within the U.S. corn belt.

Mauget found “an overall pattern of low flow

periods before 1972, and high flow periods occurring over time windows beginning after 1969.” Of the 42 stations’ high flow periods, he observed “34 occur during 1969–1998, with 25 of those periods ending in either 1997 or 1998,” and “of those 25 stations 21 are situated in the key agricultural region known as the Corn Belt.” He also found “among most of the stations in the western portions of the Corn Belt during the 1980s and 1990s there is an unprecedented tendency toward extended periods of daily high flow conditions, which lead to marked increases in the mean annual frequency of hydrological surplus conditions relative to previous years.” Furthermore, he found “in 15 of the 18 Corn Belt gage stations considered here at daily resolution, a more than 50% reduction in the mean annual incidence of hydrological drought conditions is evident during those periods.” Finally, Mauget reported “the gage station associated with the largest watershed area—the Mississippi at Vicksburg—shows more than a doubling of the mean annual frequency of hydrological surplus days during its 1973–1998 high flow period relative to previous years, and more than a 50% reduction in the mean annual incidence of hydrological drought condition.”

Mauget observed the overall pattern of climate variation “is that of a reduced tendency to hydrological drought and an increased incidence of hydrological surplus over the Corn Belt and most of the Mississippi River basin during the closing decades of the 20th century.” He further noted “some of the most striking evidence of a transition to wetter conditions in the streamflow analyses is found among streams and rivers situated along the Corn Belt’s climatologically drier western edge.”

Do such findings represent the early stages of real-world climate change? Mauget found the streamflow data do indeed “suggest a fundamental climate shift, as the most significant incidence of high ranked annual flow was found over relatively long time scales at the end of the data record.” That shift, however, is *away from* more frequent and severe drought.

Shapley *et al.* (2005) undertook a longer-term study of the topic, developing a 1,000-year hydroclimate reconstruction from local bur oak tree-ring records and various lake sediment cores in the Northern Great Plains. Prior to 1800, they determined, “droughts tended towards greater persistence than during the past two centuries,” suggesting droughts of the region became shorter-lived as opposed to longer-lasting as Earth gradually

recovered from the cold temperatures of the Little Ice Age.

Daniels and Knox (2005) analyzed the alluvial stratigraphic evidence for an episode of major channel incision in tributaries of the upper Republican River occurring between 1100 and 800 years ago, after which they compared their findings with proxy drought records from 28 other locations throughout the Great Plains and surrounding regions. This work revealed channel incision in the Republican River between approximately AD 900 and 1200 was well correlated with a multi-centennial episode of widespread drought, which in the words of Daniels and Knox “coincides with the globally recognized Medieval Warm Period.” Modern twentieth century warming has not led to a repeat of those widespread drought conditions.

Stambaugh *et al.* (2011) “used a new long tree-ring chronology developed from the central U.S. to reconstruct annual drought and characterize past drought duration, frequency, and cycles in the agriculturally important U.S. Corn Belt region during the last millennium.” They calibrated and verified this chronology against monthly values of the instrumental Palmer Hydrologic Drought Index during the summer season of June, July, and August. The six scientists reported “20th century droughts, including the Dust Bowl, were relatively unremarkable when compared to drought durations prior to the instrumental record.” They noted, for example, the nineteenth century was the driest of the past millennium, with major drought periods occurring from about 1816 to 1844 and 1849 to 1880, during what they described as the transition out of the Little Ice Age. Prior to that, there had been 45 years of drought in the latter part of the seventeenth century coincident with the Maunder Minimum of solar activity, which is associated with the coldest period of the current interglacial.

Going back further in time, Stambaugh *et al.* found an approximately 35-year drought in the mid-to late-fifteenth century during “a period of decreased radiative forcing and northern hemisphere temperatures.” Eclipsing them all, however, was “the approximately 61-year drought in the late 12th century (ca. AD 1148–1208),” which “appears to be the most significant drought of the entire reconstruction” and in fact “corresponds to the single greatest megadrought in North America during the last 2000 years (Cook *et al.*, 2007),” as well as “unmatched persistent low flows in western U.S. river basins (Meko *et al.*, 2007).” This drought, the authors

reported, occurred during the middle of the Medieval Warm Period—“an interval of warmer temperatures between approximately AD 800–1300 characterized by greater drought duration and frequency in the Northern Great plains compared to more modern times.”

Stambaugh *et al.*'s findings show there is nothing unusual, unnatural, or unprecedented about any twentieth or twenty-first century droughts that may have hit the agricultural heartland of the United States. It is also clear the much greater droughts of the past millennium occurred during periods of both relative cold and relative warmth, as well as the transitions between them.

Forman *et al.* (2005) observed “periods of dune reactivation reflect sustained moisture deficits for years to decades and reflect broader environmental change with diminished surface- and ground-water resources,” which prompted them to focus on “the largest dune system in North America, the Nebraska Sand Hills.” They utilized “recent advances in optically stimulated luminescence dating (Murray and Wintle, 2000) to improve chronologic control on the timing of dune reactivation” while linking landscape response to drought over the past 1,500 years to tree-ring records of aridity.

Forman *et al.* identified six major aeolian depositional events in the past 1,500 years, all but one of which (the 1930s “Dust Bowl” drought) occurred prior to the twentieth century. Moving back in time from the Dust Bowl, the preceding three major events occurred during the depths of the Little Ice Age, near the Little Ice Age's inception, and near the end of the Dark Ages Cold Period. As for how the earlier droughts compared with those of the past century, the researchers found the 1930s drought (the twentieth century's worst depositional event) was less severe than the others, especially the sixteenth century megadrought. Forman *et al.* concluded the aeolian landforms “are clear indicators of climate variability beyond twentieth century norms, and signify droughts of greater severity and persistence than thus far instrumentally recorded.” Their study also reveals post-Little Ice Age warming—which is often claimed to be unprecedented over the past two millennia—has not produced similarly unprecedented droughts.

Advancing the field of study back further in time, Woodhouse and Overpeck (1998) reviewed what is known about the frequency and severity of drought in the central United States over the past 2,000 years based upon empirical evidence of drought from various proxy indicators. Their study indicated the

presence of numerous “multidecadal- to century-scale droughts,” leading them to conclude “twentieth-century droughts are not representative of the full range of drought variability that has occurred over the last 2000 years.” In addition, they observed the twentieth century was characterized by droughts of “moderate severity and comparatively short duration, relative to the full range of past drought variability.”

With respect to the causes of drought, Woodhouse and Overpeck suggested there might be several either directly or indirectly inducing changes in atmospheric circulation and moisture transport. They cautioned “the causes of droughts with durations of years (i.e., the 1930s) to decades or centuries (i.e., paleodroughts) are not well understood.” Hence, they concluded, “the full range of past natural drought variability, deduced from a comprehensive review of the paleoclimatic literature, suggests that droughts more severe than those of the 1930s and 1950s are likely to occur in the future.” This is likely to be the case irrespective of future atmospheric CO₂ concentrations or temperatures.

Fritz *et al.* (2000) constructed three 2,000-year histories of lake-water salinity at three sites in North Dakota—Moon Lake, Coldwater Lake, and Rice Lake—to infer regional patterns of drought and comment on its potential cause. “From the vantage point of the 20th century,” they observed, “the three North Dakota sites suggest that droughts equal or greater in magnitude to those of the Dust Bowl period were a common occurrence during the last 2000 years and that severe droughts may have been frequent for multiple decades within this period.” In addition, they reported “studies from the northern Great Plains and western North America (Cook *et al.*, 1997; Dean, 1997; Laird *et al.*, 1996; Yu and Ito, 1999) have shown a correlation between solar forcing and centennial- and decadal-scale drought patterns.” They conclude “solar variability may influence the duration of dry periods through its impact on convective activity and circulation (Rind and Overpeck, 1993).”

Laird *et al.* (1998) examined the region's historical record of drought in an attempt to establish a baseline of natural drought variability that could help in attempts to determine whether current and future droughts might be anthropogenically influenced. Working with a high-resolution sediment core obtained from Moon Lake, North Dakota, which provided a subdecadal record of salinity (drought) over the past 2,300 years, they discovered the U.S. Northern Great Plains were relatively wet during the final 750 years of this period. Throughout the 1,550

Observations: Extreme Weather

prior years, Laird *et al.* found “recurring severe droughts were more the norm” and were “of much greater intensity and duration than any in the 20th century,” including the great Dust Bowl event of the 1930s. Consequently, and in light of their finding “no modern equivalents” to Northern Great Plains droughts experienced prior to AD 1200, it would appear twentieth century global warming has had no effect on drought conditions in this part of the world.

Tian *et al.* (2006) derived a 31-century high-resolution $\delta^{18}\text{O}$ record of aridity from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. Among their findings, they noted “the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods.” Most striking, they found “drought variability was anomalously low during the 20th century”—so depressed that “~90% of the variability values during the last 3100 years were greater than the 20th-century average.”

The above findings show there is nothing unusual, unnatural, or unprecedented about recent droughts in the Central United States. Droughts of greater duration and intensity have occurred numerous times in the past. Claims of increasing future drought as a result of global warming are not supported by real-world data, as modern global warming has, if anything, tended to lessen drought conditions throughout the central United States.

References

- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Cook, E.R., Meko, D.M., and Stockton, C.W. 1997. A new assessment of possible solar and lunar forcing of the bidecadal drought rhythm in the western United States. *Journal of Climate* **10**: 1343–1356.
- Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W. 2007. North American drought: reconstructions, causes, and consequences. *Earth Science Reviews* **81**: 93–134.
- Daniels, J.M. and Knox, J.C. 2005. Alluvial stratigraphic evidence for channel incision during the Mediaeval Warm Period on the central Great Plains, USA. *The Holocene* **15**: 736–747.
- Dean, W.E. 1997. Rates, timing, and cyclicity of Holocene eolian activity in north-central United States: Evidence from varved lake sediments. *Geology* **25**: 331–334.
- Forman, S.L., Marin, L., Pierson, J., Gomez, J., Miller, G.H., and Webb, R.S. 2005. Aeolian sand depositional records from western Nebraska: landscape response to droughts in the past 1500 years. *The Holocene* **15**: 973–981.
- Fritz, S.C., Ito, E., Yu, Z., Laird, K.R., and Engstrom, D.R. 2000. Hydrologic variation in the Northern Great Plains during the last two millennia. *Quaternary Research* **53**: 175–184.
- Gore, A. 2006. *An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It*. Rodale, Emmaus, Pennsylvania, USA.
- Karl, T., Quinlan, F., and Ezell, D.S. 1987. Drought termination and amelioration: its climatological probability. *Journal of Climate and Applied Meteorology* **26**: 1198–1209.
- Laird, K.R., Fritz, S.C., and Cumming, B.F. 1998. A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: a sub-decadal record of the last 2300 years. *Journal of Paleolimnology* **19**: 161–179.
- Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F. 1996. Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature* **384**: 552–555.
- Manabe, S., Milly, P.C.D., and Wetherald, R. 2004. Simulated long-term changes in river discharge and soil moisture due to global warming. *Hydrological Sciences Journal* **49**: 625–642.
- Manabe, S. and Wetherald, R.T. 1987. Large-scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. *Journal of the Atmospheric Sciences* **44**: 1211–1235.
- Mann, M.E. and Kump, L.R. 2008. *Dire Predictions: Understanding Global Warming*. DK Publishing Inc., New York, New York, USA.
- Mauget, S.A. 2004. Low frequency streamflow regimes over the central United States: 1939–1998. *Climatic Change* **63**: 121–144.
- Meko, D.M., Woodhouse, C.A., Baisan, C.A., Knight, T., Lukas, J.J., Hughes, M.K., and Salzer, M.W. 2007. Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters* **34**: 10.1029/2007GL029988.
- Murray, A.S. and Wintle, A.G. 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements* **32**: 57–73.
- Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., and

Ruedy, R. 1990. Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research* **95**: 9,983–10,004.

Rind, D. and Overpeck, J. 1993. Hypothesized causes of decade to century scale climate variability: Climate model results. *Quaternary Science Reviews* **12**: 357–374.

Rosenzweig, C. and Hillel, D. 1993. The Dust Bowl of the 1930s: Analog of greenhouse effect in the Great Plains? *Journal of Environmental Quality* **22**: 9–22.

Shapley, M.D., Johnson, W.C., Engstrom, D.R., and Osterkamp, W.R. 2005. Late-Holocene flooding and drought in the Northern Great Plains, USA, reconstructed from tree rings, lake sediments and ancient shorelines. *The Holocene* **15**: 29–41.

Soule, P.T. 1992. Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions. *International Journal of Climatology* **12**: 11–24.

Stambaugh, M.C., Guyette, R.P., McMurtry, E.R., Cook, E.R., Meko, D.M., and Lupo, A.R. 2011. Drought duration and frequency in the U.S. Corn Belt during the last millennium (AD 992–2004). *Agricultural and Forest Meteorology* **151**: 154–162.

Tian, J., Nelson, D.M., and Hu, F.S. 2006. Possible linkages of late-Holocene drought in the North American mid-continent to Pacific Decadal Oscillation and solar activity. *Geophysical Research Letters* **33**: 10.1029/2006GL028169.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

Yu, Z.C. and Ito, E. 1999. Possible solar forcing of century-scale drought frequency in the northern Great Plains. *Geology* **27**: 263–266.

7.4.4.3.2 Eastern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the eastern United States.

Pederson *et al.* (2012) note drought is “a pervasive phenomenon throughout much of North America with profound ecological and societal implications,” as has been suggested by the work of Hursh and Haasis (1931), Breshears *et al.* (2005),

Manuel (2008), and Allen *et al.* (2010). Citing Knight (2004) and Seager *et al.* (2009), they report recent moisture deficits in the southeastern United States have renewed water management challenges that underscore the need to “better understand drought processes in humid, subtropical regions.” Pederson *et al.* attempted “to put the region’s recent drought variability in a long-term perspective” by reconstructing historic drought trends in the Apalachicola-Chattahoochee-Flint river basin over the period 1665–2010 using a dense and diverse tree-ring network. This network, they wrote, “accounts for up to 58.1% of the annual variance in warm-season drought during the 20th century and captures wet eras during the middle to late 20th century.”

The 12 researchers found the Palmer Drought Severity Index reconstruction for their study region revealed “recent droughts are not unprecedented over the last 346 years” and “droughts of extended duration occurred more frequently between 1696 and 1820,” when most of the world was in the midst of the Little Ice Age. They also found their results “confirm the findings of the first reconstruction of drought in the southern Appalachian Mountain region, which indicates that the mid-18th and early 20th centuries were the driest eras since 1700,” citing Stahle *et al.* (1988), Cook *et al.* (1998), and Seager *et al.* (2009).

Quiring (2004) introduced his study of the subject by describing the drought of 2001–2002, which by June of the latter year produced anomalously dry conditions along most of the east coast of the country, including severe drought conditions from New Jersey to northern Florida forcing 13 states to ration water. Shortly after the drought began to subside in October 2002, however, moist conditions returned and persisted for about a year, producing the wettest growing-season of the instrumental record. These observations, in Quiring’s words, “raise some interesting questions,” including, “are moisture conditions in this region becoming more variable?”

Using an 800-year tree-ring-based reconstruction of the Palmer Hydrological Drought Index, Quiring documented the frequency, severity, and duration of growing-season moisture anomalies in the southern mid-Atlantic region of the United States. Among other things, this work revealed “conditions during the 18th century were much wetter than they are today, and the droughts that occurred during the 16th century tended to be both longer and more severe.” He concluded “the recent growing-season moisture anomalies that occurred during 2002 and 2003 can

Observations: Extreme Weather

only be considered rare events if they are evaluated with respect to the relatively short instrumental record (1895–2003).” When compared to the 800-year reconstructed record, he observed, “neither of these events is particularly unusual.” In addition, Quiring reported, “although climate models predict decreases in summer precipitation and significant increases in the frequency and duration of extreme droughts, the data indicate that growing-season moisture conditions during the 20th century (and even the last 19 years) appear to be near normal (well within the range of natural climate variability) when compared to the 800-year record.”

Cronin *et al.* (2000) studied the salinity gradient across sediment cores from Chesapeake Bay, the largest estuary in the United States, in an effort to examine precipitation variability in the surrounding watershed during the past millennium. Their work revealed the existence of a high degree of decadal and multidecadal variability between wet and dry conditions throughout the 1,000-year record, when regional precipitation totals fluctuated by 25 to 30%, often in “extremely rapid [shifts] occurring over about a decade.” In addition, precipitation over the last two centuries of the record was generally greater than it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the local climate was found to be “extremely wet.” The 10 researchers also found the region experienced several “megadroughts” that lasted for 60 to 70 years, several of which were “more severe than twentieth century droughts.”

Willard *et al.* (2003) built upon the work of Cronin *et al.*, examining the last 2,300 years of the Holocene record for Chesapeake Bay and the adjacent terrestrial ecosystem “through the study of fossil dinoflagellate cysts and pollen from sediment cores.” They found “several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records.” The first of these periods of lower-than-average precipitation (200 BC–AD 300) occurred during the latter part of the Roman Warm Period, and the next such period (~AD 800–1200) “corresponds to the ‘Medieval Warm Period.’” In addition, they identified several decadal-scale dry intervals spanning the years AD 1320–1400 and 1525–1650.

Willard *et al.* noted “mid-Atlantic dry periods generally correspond to central and southwestern USA ‘megadroughts’, which are described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded

twentieth-century droughts in severity.” They observed “droughts in the late sixteenth century that lasted several decades, and those in the ‘Medieval Warm Period’ and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al.*, 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al.*, 2000; Laird *et al.*, 1996a, 1996b) and detrital clastic records (Dean, 1997).” Their work in the eastern United States, together with the work of researchers in other parts of the country, demonstrates twentieth-century global warming has not led to the occurrence of unusually strong wet or dry periods.

Springer *et al.* (2008) constructed a multidecadal-scale history of east-central North America’s hydroclimate covering the past 7,000 years, based on Sr/Ca ratios and $\delta^{13}\text{C}$ data obtained from stalagmite BCC-002 of Buckeye Creek Cave (BCC) in West Virginia, USA. The authors detected seven significant mid- to late-Holocene droughts that “correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle,” as per Bond *et al.* (1997, 2001). In addition, they found “the Sr/Ca and $\delta^{13}\text{C}$ time series display periodicities of ~200 and ~500 years,” “the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle,” and the ~500-year periodicity is likely “a harmonic of the IRD oscillations.” They also reported “cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years,” and these latter values “are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500 -years IRD periodicity.” Such findings “corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau *et al.*, 2002; Willard *et al.*, 2005; Denniston *et al.*, 2007).” Their high-resolution time series also “provide much stronger evidence in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results.”

Palaeoclimate data from the eastern United States, as highlighted in this section, show droughts are not becoming more extreme and erratic in response to global warming.

References

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling,

Climate Change Reconsidered II

- A., Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J., Allard, G., Running, S.W., Semerci, A., and Cobb, N. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**: 660–684.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B., and Meyer, C.W. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences USA* **102**: 15,144–15,148.
- Cook, E.R., Kahlack, M.A., and Jacoby, G.C. 1988. The 1986 drought in the southeastern United States—how rare an event was it? *Journal of Geophysical Research* **93**: 14,257–14,260.
- Cronin, T., Willard, D., Karlsen, A., Ishman, S., Verardo, S., McGeehin, J., Kerhin, R., Holmes, C., Colman, S., and Zimmerman, A. 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. *Geology* **28**: 3–6.
- Dean, W.E. 1997. Rates, timing, and cyclicity of Holocene aeolian activity in north-central United States: evidence from varved lake sediments. *Geology* **25**: 331–334.
- Denniston, R.F., DuPree, M., Dorale, J.A., Asmerom, Y., Polyak, V.J., and Carpenter, S.J. 2007. Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central Missouri, USA. *Quaternary Research* **68**: 45–52.
- Fritz, S.C., Ito, E., Yu, Z., Laird, K.R., and Engstrom, D.R. 2000. Hydrologic variation in the northern Great Plains during the last two millennia. *Quaternary Research* **53**: 175–184.
- Hursh, C.R. and Haasis, F.W. 1931. Effects of 1925 summer drought on southern Appalachian hardwoods. *Ecology* **12**: 380–386.
- Knight, T. 2004. *Reconstruction of Flint River Streamflow Using Tree-Rings*. Water Policy Working Paper 2004/2005. Georgia Water Policy and Planning Center, Albany, Georgia, USA.
- Laird, K.R., Fritz, S.C., Grimm, E.C., and Mueller, P.G. 1996a. Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains. *Limnology and Oceanography* **41**: 890–902.
- Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F. 1996b. Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature* **384**: 552–554.
- Manuel, J. 2008. Drought in the southeast: lessons for water management. *Environmental and Health Perspectives* **116**: A168–A171.
- Pederson, N., Bell, A.R., Knight, T.A., Leland, C., Malcomb, N., Anchukaitis, K.J., Tackett, K., Scheff, J., Brice, A., Catron, B., Blozan, W., and Riddle, J. 2012. A long-term perspective on a modern drought in the American Southeast. *Environmental Research Letters* **7**: 10.1088/1748-9326/7/1/014034.
- Quiring, S.M. 2004. Growing-season moisture variability in the eastern USA during the last 800 years. *Climate Research* **27**: 9–17.
- Seager, R., Tzanova, A., and Nakamura, J. 2009. Drought in the southeastern United States: causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate* **22**: 5021–5045.
- Springer, G.S., Rowe, H.D., Hardt, B., Edwards, R.L., and Cheng, H. 2008. Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America. *Geophysical Research Letters* **35**: 10.1029/2008GL034971.
- Stahle, D.W. and Cleaveland, M.K. 1994. Tree-ring reconstructed rainfall over the southeastern U.S.A. during the Medieval Warm Period and Little Ice Age. *Climatic Change* **26**: 199–212.
- Stahle, D.W., Cleaveland, M.K., and Hehr, J.G. 1985. A 450-year drought reconstruction for Arkansas, United States. *Nature* **316**: 530–532.
- Stahle, D.W., Cleaveland, M.K., and Hehr, J.G. 1988. North Carolina climate changes reconstructed from tree rings: AD 372–1985. *Science* **240**: 1517–1519.
- Viau, A.E., Gajewski, K., Fines, P., Atkinson, D.E., and Sawada, M.C. 2002. Widespread evidence of 1500 yr climate variability in North America during the past 14,000 yr. *Geology* **30**: 455–458.
- Willard, D.A., Bernhardt, C.E., Korejwo, D.A., and Meyers, S.R. 2005. Impact of millennial-scale Holocene climate variability on eastern North American terrestrial ecosystems: pollen-based climatic reconstruction. *Global and Planetary Change* **47**: 17–35.
- Willard, D.A., Cronin, T.M., and Verardo, S. 2003. Late-

Observations: Extreme Weather

Holocene climate and ecosystem history from Chesapeake Bay sediment cores, USA. *The Holocene* **13**: 201–214.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the Central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

7.4.4.3.3 Western

7.4.4.3.3.1 Pacific Northwest

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Pacific Northwest region of the United States.

Knapp *et al.* (2002) created a 500-year history of severe single-year Pacific Northwest droughts from a study of 18 western juniper tree-ring chronologies identifying what they call extreme Climatic Pointer Years, or CPYs, indicative of severe single-year droughts. This procedure revealed “widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries,” and “both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread.” Thereafter, however, “CPYs became more numerous during the 20th century,” although the number of twentieth century extreme CPYs (26) was still substantially less than the mean of sixteenth and seventeenth century extreme CPYs (38), when the planet was considerably colder.

Gedalof *et al.* (2004) used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water-year flow since 1750 on the Columbia River at The Dales in Oregon. They conducted this study of the second largest drainage basin in the United States “for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events.” The study revealed “persistent low flows during the 1840s were probably the most severe of the past 250 years” and “the drought of the 1930s is probably the second most severe.”

More recent droughts, in the words of the researchers, “have led to conflicts among uses (e.g., hydroelectric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of

access to water (in particular junior water rights holders in the agricultural sector).” Nevertheless, they observed, “these recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events.” They also found “the period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events,” demonstrating Pacific Northwest droughts have not become more severe or long-lasting as temperatures rose during the twentieth century.

References

Gedalof, Z., Peterson, D.L., and Mantua, N.J. 2004. Columbia River flow and drought since 1750. *Journal of the American Water Resources Association* **40**: 1579–1592.

Knapp, P.A., Grissino-Mayer, H.D., and Soule, P.T. 2002. Climatic regionalization and the spatio-temporal occurrence of extreme single-year drought events (1500–1998) in the interior Pacific Northwest, USA. *Quaternary Research* **58**: 226–233.

7.4.4.3.3.2 Idaho/Montana/Wyoming

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Idaho, Montana, and Wyoming in the United States.

Wise (2010) noted “the 1667 km Snake River is one of the largest rivers in the United States, draining a semiarid region that covers 283,000 km² [and] includes most of Idaho, as well as portions of Wyoming, Utah, Nevada, Oregon, and Washington.” She observed the river’s water has been “historically allocated almost entirely for agricultural irrigation” and the Snake River is “the largest tributary of the Columbia River (based on both discharge and watershed size),” which makes it “also important for users further downstream.” Wise reported “the 20th century was an abnormally wet period in this region (Gray and McCabe, 2010),” but an early twenty-first century drought “has raised questions about whether these dry conditions should be considered an extreme event or if this drought is within the range of natural variability.”

Wise utilized tree-ring samples collected near the headwaters of the Snake River in Wyoming augmented with preexisting tree ring chronologies to

extend the short (1911–2006) instrumental water supply record of the region. This provided the first multi-century (1591–2005) record of the river's water supply variability, which could then provide context for the early twenty-first century drought in this region. She found “individual low-flow years in 1977 and 2001 and the longer-term 1930s Dust Bowl drought meet or exceed the magnitude of dry periods in the extended reconstructed period.” In terms of overall severity, “the instrumental record does not contain a drought of the extent seen in the mid-1600s.” Wise further observed “twenty-four of 34 years in the 1626–1659 time period had below-average flow, including periods of six and seven consecutive below-mean years (1626–1632 and 1642–1647),” and “during the most severe period from 1626 to 1647, 17 of 22 years (77%) were below-normal flow.” She concluded “this type of event could represent a new ‘worst-case scenario’ for water planning in the upper Snake River.”

Gray *et al.* (2004) used cores and cross sections from 79 Douglas fir and limber pine trees at four sites in the Bighorn Basin of north-central Wyoming and south-central Montana to develop a proxy for annual precipitation spanning the period AD 1260–1998. This reconstruction, in their words, “exhibits considerable nonstationarity, and the instrumental era (post-1900) in particular fails to capture the full range of precipitation variability experienced in the past ~750 years.” They found “both single-year and decadal-scale dry events were more severe before 1900” and “dry spells in the late thirteenth and sixteenth centuries surpass both [the] magnitude and duration of any droughts in the Bighorn Basin after 1900.” They observed “single- and multi-year droughts regularly surpassed the severity and magnitude of the ‘worst-case scenarios’ presented by the 1930s and 1950s droughts.”

In a study covering a much longer period of time, Persico and Meyer (2009) studied “beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park.” They compared “the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region,” finding “gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP are contemporaneous with increased charcoal

accumulation rates in Yellowstone lakes and peaks in fire-related debris-flow activity, inferred to reflect severe drought and warmer temperatures (Meyer *et al.*, 1995).” In addition, they noted “the lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly, a time of widespread multi-decadal droughts and high climatic variability in Yellowstone National Park (Meyer *et al.*, 1995) and the western USA (Cook *et al.*, 2004; Stine, 1998; Whitlock *et al.*, 2003).” The lack of evidence for beaver activity 2200–1800 cal yr BP is concurrent with the Roman Warm Period. In both of these periods, the researchers concluded, the severe droughts “likely caused low to ephemeral discharges in smaller streams, as in modern severe drought,” implying the Medieval and Roman Warm Periods were likely just as dry and warm as it is today.

These findings suggest there is nothing unusual, unnatural, or unprecedented about the degree of warmth and drought in the Current Warm Period. The regular recurrence of such drought conditions suggests their cause is a cyclical phenomenon of nature independent of the activities of the planet's human population.

References

- Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Gray, S.T., Fastie, C.L., Jackson, S.T., and Betancourt, J.L. 2004. Tree-ring-based reconstruction of precipitation in the Bighorn Basin, Wyoming, since 1260 A.D. *Journal of Climate* **17**: 3855–3865.
- Gray, S.T. and McCabe, G.J. 2010. A combined water balance and tree ring approach to understanding the potential hydrologic effects of climate change in the central Rocky Mountain region. *Water Resources Research* **46**: 10.1029/2008WR007650.
- Meyer, G.A., Wells, S.G., and Jull, A.J.T. 1995. Fire and alluvial chronology in Yellowstone National Park—climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin* **107**: 1211–1230.
- Persico, L. and Meyer, G. 2009. Holocene beaver damming, fluvial geomorphology, and climate in Yellowstone National Park, Wyoming. *Quaternary Research* **71**: 340–353.
- Stine, S. 1998. Medieval climatic anomaly in the Americas. In: Issar, A.S. and Brown, N. (Eds.) *Water, Environment*

and Society in Times of Climatic Change. Kluwer Academic Publishers, pp. 43–67.

Whitlock, C., Shafer, S.L., and Marlon, J. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management* **178**: 5–21.

Wise, E.K. 2010. Tree ring record of streamflow and drought in the upper Snake River. *Water Resources Research* **46**: 10.1029/2009WR009282.

7.4.4.3.3 Nevada/Utah

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Nevada and Utah in the United States.

Benson *et al.* (2002) developed continuous high-resolution $\delta^{18}\text{O}$ records from cored sediments of Pyramid Lake, Nevada, which they used to help construct a 7,600-year history of droughts throughout the surrounding region. Oscillations in the hydrologic balance evident in this record occurred, on average, about every 150 years, but with significant variability. Over the most recent 2,740 years, for example, intervals between droughts ranged from 80 to 230 years, and drought durations ranged from 20 to 100 years. Some of the larger droughts forced mass migrations of indigenous peoples from lands that could no longer support them. In contrast, droughts of the historical instrumental record typically have lasted less than a decade.

Mensing *et al.* (2004) analyzed sediment cores for pollen and algal microfossils deposited at Pyramid Lake, Nevada during the prior 7,630 years, which allowed them to infer the hydrologic history of the area over that period. They found “sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet,” but “the past 2500 yr have been marked by recurring persistent droughts.” The longest of these droughts “occurred between 2500 and 2000 cal yr B.P.,” and others occurred “between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P.,” with none recorded in more recent, warmer times.

The researchers also noted “the timing and magnitude of droughts identified in the pollen record compare favorably with previously published $\delta^{18}\text{O}$ data from Pyramid Lake” and with “the ages of

submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada.” Finally, noting Bond *et al.* (2001) “found that over the past 12,000 yr, decreases in [North Atlantic] drift ice abundance corresponded to increased solar output,” they reported when they “compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice ... nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record.” Mensing *et al.* concluded “changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States].”

Gray *et al.* (2004) used samples from 107 piñon pines at four sites in Utah to develop a proxy record of annual precipitation spanning the AD 1226–2001 interval for the Uinta Basin watershed in the northeastern portion of the state. This revealed “single-year dry events before the instrumental period tended to be more severe than those after 1900” and decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found “dry events in the late 13th, 16th, and 18th Centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900.”

Considering the other end of the moisture spectrum, Gray *et al.* reported the twentieth century was host to two of the strongest wet intervals (1938–1952 and 1965–1987), although these periods were only the seventh and second most intense wet regimes, respectively, of the entire record. It would appear precipitation extremes (both high and low) in northeastern Utah’s Uinta Basin have become more attenuated as opposed to more amplified in conjunction with twentieth-century global warming.

MacDonald and Tingstad (2007) examined instrumental climate records to outline historical spatiotemporal patterns of precipitation variability in the Uinta Mountains, after which they “used tree-ring width chronologies from *Pinus edulis* Engelm (two-needle pinyon pine) trees growing near the northern and southern flanks of the mountains to produce an ~600-year reconstruction (AD 1405–2001) of Palmer Drought Severity Index [PDSI] for Utah Climate Division 5,” which they say “allows for the placement of 20th century droughts within the longer context of natural drought variability and also allows for the detection of long-term trends in drought.”

MacDonald and Tingstad reported “in the context

of prolonged severe droughts,” the twentieth century “has been relatively moist compared to preceding centuries.” The scientists reported their PDSI reconstruction and the Uinta Basin precipitation reconstruction indicate “the early to mid 17th century in particular, and portions of the 18th and 19th centuries, experienced prolonged (>10 years) dry conditions that would be unusually severe by 20th century standards.” They noted “the most striking example of widespread extended drought occurred during a ~45-year period between 1625 and 1670 when PDSI only rarely rose above negative values.”

References

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., and Lindstrom, S. 2002. Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada. *Quaternary Science Reviews* **21**: 659–682.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Gray, S.T., Jackson, S.T., and Betancourt, J.L. 2004. Tree-ring based reconstructions of interannual to decadal scale precipitation variability for northeastern Utah since 1226 A.D. *Journal of the American Water Resources Association* **40**: 947–960.

MacDonald, G.M. and Tingstad, A.H. 2007. Recent and multicentennial precipitation variability and drought occurrence in the Uinta Mountains region, Utah. *Arctic, Antarctic, and Alpine Research* **39**: 549–555.

Mensing, S.A., Benson, L.V., Kashgarian, M., and Lund, S. 2004. A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. *Quaternary Research* **62**: 29–38.

7.4.4.3.4 California

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to California in the United States.

Malamud-Roam *et al.* (2006) conducted an extensive review of “the variety of paleoclimatic resources for the San Francisco Bay and watershed in

order to identify major climate variations in the pre-industrial past, and to compare the records from the larger watershed region with the Bay records in order to determine the linkages between climate experienced over the larger watershed region and conditions in the San Francisco Bay.” They found “intermittent mega-droughts of the Medieval Climate Anomaly (ca. AD 900–1350) coincided with a period of anomalously warm coastal ocean temperatures in the California Current,” and “oxygen isotope compositions of mussel shells from archaeological sites along the central coast also indicate that sea surface temperatures were slightly warmer than present.” In contrast, they noted “the Little Ice Age (ca. AD 1450–1800) brought unusually cool and wet conditions to much of the watershed,” and “notably stable conditions have prevailed over the instrumental period, i.e., after ca. AD 1850, even including the severe, short-term anomalies experienced during this period,” namely, “the severe droughts of the 1930s and the mid-1970s.” When longer paleoclimate records are considered, they noted, “current drought conditions experienced in the US Southwest do not appear out of the range of natural variability.” However, they speculated, “warmer temperatures associated with anthropogenic global warming may exacerbate such conditions,” which would suggest current temperatures are not as warm as during the Medieval Warm Period.

In a study of “perfect drought” in Southern California (USA), MacDonald *et al.* (2008) defined the term as “a prolonged drought that affects southern California, the Sacramento River basin and the upper Colorado River basin simultaneously.” They noted the instrumental record indicates the occurrence of such droughts throughout the past century, but they “generally persist for less than five years.” That they have occurred at all, however, suggests the possibility of even longer perfect droughts, which could prove catastrophic for the region.

The three researchers explored the likelihood of such droughts occurring in the future based on dendrochronological reconstructions of the winter Palmer Drought Severity Index (PDSI) in southern California over the past thousand years, plus the concomitant annual discharges of the Sacramento and Colorado Rivers, under the logical assumption that what has occurred before may occur again. MacDonald *et al.* reported finding “prolonged perfect droughts (~30–60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th

Observations: Extreme Weather

century during the period of the so-called ‘Medieval Climate Anomaly.’” This led them to conclude “prolonged perfect droughts due to natural or anthropogenic changes in radiative forcing, are a clear possibility for the near future.”

Kleppe *et al.* (2011) reconstructed the duration and magnitude of extreme droughts in the northern Sierra Nevada region based on dendrochronology, geomorphic analysis, and hydrologic modeling of the Fallen Leaf Lake (California) watershed in order to estimate paleo-precipitation near the headwaters of the Truckee River-Pyramid Lake watershed of eastern California and northwestern Nevada. The six scientists found “submerged Medieval trees and geomorphic evidence for lower shoreline corroborate a prolonged Medieval drought near the headwaters of the Truckee River-Pyramid Lake watershed,” and water-balance calculations independently indicated precipitation was “less than 60% normal.” They noted these findings “demonstrate how prolonged changes of Fallen Leaf’s shoreline allowed the growth and preservation of Medieval trees far below the modern shoreline.” In addition, they noted age groupings of such trees suggest similar megadroughts “occurred every 600–1050 years during the late Holocene.”

The findings of Kleppe *et al.*, and many others whose works they cite, suggest the Medieval Warm Period experienced substantially less precipitation and far longer and more severe drought than what has been experienced to date in the Current Warm Period. In addition, their data suggest such dry conditions have occurred regularly, in cyclical fashion, “every 650–1150 years during the mid- and late-Holocene.” These observations suggest there is nothing unusual, unnatural, or unprecedented about the nature of drought during the Current Warm Period in the western United States.

References

Kleppe, J.A., Brothers, D.S., Kent, G.M., Biondi, F., Jensen, S., and Driscoll, N.W. 2011. Duration and severity of Medieval drought in the Lake Tahoe Basin. *Quaternary Science Reviews* **30**: 3269–3279.

MacDonald, G.M., Kremenetski, K.V., and Hidalgo, H.G. 2008. Southern California and the perfect drought: Simultaneous prolonged drought in Southern California and the Sacramento and Colorado River systems. *Quaternary International* **188**: 11–23.

Malamud-Roam, F.P., Ingram, B.L., Hughes, M., and Florsheim, J.L. 2006. Holocene paleoclimate records from

a large California estuarine system and its watershed region: linking watershed climate and bay conditions. *Quaternary Science Reviews* **25**: 1570–1598.

7.4.4.3.3.5 Colorado/Colorado River Basin

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Colorado and the Colorado River Basin of the United States.

Hidalgo *et al.* (2000) used a new form of principal components analysis to reconstruct a history of streamflow for the Upper Colorado River Basin based on information obtained from tree-ring data, after which they compared their results to those of Stockton and Jacoby (1976). They found the two approaches yielded similar results, except Hidalgo *et al.*’s approach responded with more intensity to periods of below-average streamflow or regional drought. Thus it was easier for them to determine there has been “a near-centennial return period of extreme drought events in this region,” going back to the early 1500s.

Woodhouse *et al.* (2006) also generated proxy reconstructions of water-year streamflow for the Upper Colorado River Basin, based on four key gauges (Green River at Green River, Utah; Colorado River near Cisco, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona) and using an expanded tree-ring network and longer calibration records than in previous efforts. They found the major drought of 2000–2004, “as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record” and “average reconstructed annual flow for the period 1844–1848 was lower.” They reported “two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004,” and six other periods “have a 10% or greater chance of being drier.” In addition, their work revealed “longer duration droughts have occurred in the past” and “the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906–1995 average.”

“Overall,” the three researchers observed, “these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River

hydroclimate.” Woodhouse *et al.* concluded “droughts more severe than any 20th to 21st century event occurred in the past,” a finding entirely contrary to the climate model projection that global warming promotes longer-lasting droughts of greater severity. The real-world record of Upper Colorado River Basin droughts instead suggests such climatic conditions are more strongly associated with the much colder temperatures that characterized the Little Ice Age.

Woodhouse and Lukas (2006) developed “a network of 14 annual streamflow reconstructions, 300–600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies.” Their expanded streamflow reconstructions indicated “the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries.” The scientists reported “multi-year drought events more severe than the 1950s drought have occurred” and “the greatest frequency of extreme low flow events occurred in the 19th century,” with a “clustering of extreme event years in the 1840s and 1850s.”

Meko *et al.* (2007) used a newly developed network of tree-ring sites located within the Upper Colorado River Basin, consisting of tree-ring samples from living trees augmented by similar samples obtained from logs and dead standing trees (remnant wood), to extend the record of reconstructed annual flows of the Colorado River at Lees Ferry, Arizona, into the Medieval Warm Period, during which they say “epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North America.”

“The most prominent feature of the smoothed long-term reconstruction,” Meko *et al.* write, “is the major period of low flow in the mid-1100s,” which “25-year running mean occurred in AD 1130–1154.” For this level of smoothing, they reported, “conditions in the mid-1100s in the UCRB were even drier than during the extremely widespread late-1500s North American mega-drought (e.g., Stahle *et al.*, 2000).” For comparison, they observed “if ‘normal’ is defined as the observed mean annual flow for 1906–2004, the anomalous flow for AD 1130–1154 was less than 84% of normal,” whereas “the lowest 25-year mean of observed flows (1953–1977) was 87% of normal.” The authors further noted the 80% confidence band of their data “suggests a greater than 10% probability that the true mean for AD 1130–1154 was as low as 79% of normal.” Additionally, the seven scientists reported “a detailed view of the time series of annual

reconstructed flow reveals that the mid-1100s is characterized by a series of multi-year low-flow pluses imbedded in a generally dry 62-year period (1118–1179),” and “the key drought signature is a stretch of 13 consecutive years of below normal flow (1143–1155).” They also noted “in no other period of the reconstruction was flow below normal for more than 10 consecutive years, and the longest stretch of consecutive dry years in the reconstruction for the modern instrumental period (post 1905) was just 5 years.”

Gray *et al.* (2011) observed “over the past decade severe drought conditions in the western United States have driven a growing interest in the range of natural hydrologic variability that has occurred over past centuries to millennia,” as have “concerns related to the detection and prediction of anthropogenic climate-change impacts.” The authors noted in order to know how unusual or unprecedented certain aspects of climate may have been recently, one must know how they varied over past centuries to millennia, when man’s influence on them was minimal or non-existent. Against this backdrop, the three U.S. researchers derived millennial-length records of water year (October–September) streamflow for three key Upper Colorado River tributaries—the White, Yampa, and Little Snake Rivers—based on tree-ring data they obtained from 75 preexistent chronologies for sites scattered throughout the region, where each chronology was derived from average annual ring-widths of at least 15 and as many as 80 trees per site.

They found “as in previous studies focused on the Upper Colorado River system as a whole (e.g., Meko *et al.*, 2007),” the sub-basin reconstructions “show severe drought years and extended dry periods well outside the range of observed flows.” Although they noted 1902 and 2002 “were among the most severe in the last ~1,000 years,” they found “pre-instrumental dry events often lasted a decade or longer with some extended low-flow regimes persisting for 30 years or more.” In addition, their research “shows anomalous wetness in the 20th century, a finding that has been well documented in the Colorado River basin and surrounding areas (Gray *et al.*, 2004, 2007; Woodhouse *et al.*, 2006; Watson *et al.*, 2009).”

In an additional study from the Colorado Plateau region with implications for drought in the entire western United States, Routson *et al.* (2011) reported “many southwestern United States high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than

we have experienced during the historical period (e.g., Woodhouse and Overpeck, 1998; Cook *et al.*, 2004, 2010; Meko *et al.*, 2007).” They observed “the medieval interval (ca. AD 900 to 1400), a period with relatively warm Northern Hemisphere temperatures, has been highlighted as a period in western North America with increased drought severity, duration and extent (e.g., Stine, 1994; Cook *et al.*, 2004, 2010; Meko *et al.*, 2007; Woodhouse *et al.*, 2010),” and “the mid-12th century drought associated with dramatic decreases in Colorado River flow (Meko *et al.*, 2007), and the ‘Great Drought’ associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region (Douglass, 1929), all occurred during the medieval period.” These observations suggest significant Northern Hemispheric warmth tends to produce western North America megadroughts.

Routson *et al.* used a new tree-ring record derived from living and remnant bristlecone pine wood from the headwaters region of the Rio Grande River in Colorado (USA), along with other regional records, to evaluate “periods of unusually severe drought over the past two millennia (268 BC to AD 2009).” The three researchers reported their work “reveals two periods of enhanced drought frequency and severity relative to the rest of the record,” and “the later period, AD ~1050–1330, corresponds with medieval aridity well documented in other records.” The researchers reported “the earlier period is more persistent (AD ~1–400), and includes the most pronounced event in the ... chronology: a multi-decadal-length drought during the 2nd century,” which “includes the unsmoothed record’s driest 25-year interval (AD 148–173) as well as a longer 51-year period, AD 122–172, that has only two years with ring width slightly above the long-term mean,” Also, “the smoothed chronology shows the periods AD 77–282 and AD 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-year record.” They observed this second century drought “impacted a region that extends from southern New Mexico north and west into Idaho.”

Routson *et al.* reported “reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity,” and “available data also suggest that the Northern Hemisphere may have been warm during both intervals.” Routson *et al.* suggested the southwestern United States could experience similar or even more severe megadroughts

in the future, as they suspect it will continue to warm in response to continued anthropogenic CO₂ emissions. If global warming is in fact the major cause of western USA drought, then it must be significantly cooler now than it was during those two prior multicentury warm periods, since we have not yet experienced droughts anywhere near the severity or duration of those that occurred in the Roman and Medieval Warm Periods.

References

- Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S., Herweijer, C., and Woodhouse, C. 2010. Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* **25**: 48–61.
- Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Douglass, A.E. 1929. The secret of the Southwest solved with talkative tree rings. *National Geographic* **December**: 736–770.
- Gray, S.T., Graumlich, L.J., and Betancourt, J.L. 2007. Annual precipitation in the Yellowstone National Park region since CE 1173. *Quaternary Research* **68**: 18–27.
- Gray, S.T., Jackson, S.T., and Betancourt, J.L. 2004. Tree-ring based reconstructions of interannual to decadal scale precipitation variability for northeastern Utah since 1226 A.D. *Journal of the American Water Resources Association* **40**: 947–960.
- Gray, S.T., Lukas, J.J., and Woodhouse, C.A. 2011. Millennial-length records of streamflow from three major Upper Colorado River tributaries. *Journal of the American Water Resources Association* **47**: 702–712.
- Hidalgo, H.G., Piechota, T.C., and Dracup, J.A. 2000. Alternative principal components regression procedures for dendrohydrologic reconstructions. *Water Resources Research* **36**: 3241–3249.
- Meko, D.M., Woodhouse, C.A., Baisan, C.A., Knight, T., Lukas, J.J., Hughes, M.K., and Salzer, M.W. 2007. Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters* **34**: 10.1029/2007GL029988.
- Routson, C.C., Woodhouse, C.A., and Overpeck, J.T. 2011. Second century megadrought in the Rio Grande headwaters, Colorado: How unusual was medieval drought? *Geophysical Research Letters* **38**: 10.1029/2011GL050015.
- Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell, M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and

Luckman, B.H. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, Transactions, American Geophysical Union* **81**: 121–125.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.

Stockton, C.W. and Jacoby Jr., G.C. 1976. Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin based on tree-ring analysis. *Lake Powell Research Project Bulletin* **18**, Institute of Geophysics and Planetary Physics, University of California, Los Angeles.

Watson, T.A., Barnett, F.A., Gray, S.T., and Tootle, G.A. 2009. Reconstructed stream flows for the headwaters of the Wind River, Wyoming, USA. *Journal of the American Water Resources Association* **45**: 224–236.

Woodhouse, C.A., Gray, S.T., and Meko, D.M. 2006. Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research* **42**: 10.1029/2005WR004455.

Woodhouse, C.A. and Lukas, J.J. 2006. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change* **78**: 293–315.

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W., and Cook, E.R. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences USA* **107**: 21,283–21,288.

Woodhouse, C.A. and Overpeck, J.T. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society* **79**: 2693–2714.

7.4.4.3.3.6 Arizona/New Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Arizona and New Mexico region of the United States.

Ni *et al.* (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division of Arizona and New Mexico from a network of 19 tree-ring chronologies. They determined “sustained dry periods comparable to the 1950s drought” occurred in “the late 1000s, the mid 1100s, 1570–97, 1664–70, the 1740s, the 1770s, and

the late 1800s.” They also noted the 1950s drought “only lasted from approximately 1950 to 1956,” whereas the sixteenth-century megadrought lasted more than four times longer.

Rasmussen *et al.* (2006) derived a record of regional relative moisture from variations in the annual band thickness and mineralogy of two columnar stalagmites collected from Carlsbad Cavern and Hidden Cave in the Guadalupe Mountains near the New Mexico/Texas border. They discovered both records “suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record,” confirming the significant droughts and floods of recent times are certainly not unprecedented during the past millennium or more.

References

Ni, F., Cavazos, T., Hughes, M.K., Comrie, A.C., and Funkhouser, G. 2002. Cool-season precipitation in the southwestern USA since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* **22**: 1645–1662.

Rasmussen, J.B.T., Polyak, V.J., and Asmerom, Y. 2006. Evidence for Pacific-modulated precipitation variability during the late Holocene from the southwestern USA. *Geophysical Research Letters* **33**: 10.1029/2006GL025714.

7.4.4.3.3.7 Multiple States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to multiple-state regions in the western United States.

Several studies have examined historical drought trends across multiple states in the western United States. Gray *et al.* (2003), for example, examined 15 tree ring-width chronologies used in previous reconstructions of drought for evidence of low-frequency variations in five regional composite precipitation histories in the central and southern Rocky Mountains. They found “strong multidecadal phasing of moisture variation was present in all regions during the late 16th-century megadrought,” and “oscillatory modes in the 30–70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at

some sites until the 1950s drought.” They speculated “severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase Pacific Decadal Oscillation with the warm phase Atlantic Multidecadal Oscillation,” which they envisioned as having happened in both the severe 1950s drought and the late sixteenth-century megadrought. This suggests episodes of extreme dryness in this part of the country may be driven in part by naturally recurring climate “regime shifts” in the Pacific and Atlantic Oceans.

Seager (2007) also suggested ocean oscillations might bear a good deal of the blame for large-scale drought in the western United States. Seager studied the global context of the drought that affected nearly the entire United States, northern Mexico, and the Canadian Prairies—but most particularly the American West—between 1998 and 2004. Based on atmospheric reanalysis data and ensembles of climate model simulations forced by global or tropical Pacific sea surface temperatures over the period January 1856 to April 2005, Seager compared the climatic circumstances of the recent drought with those of the five prior great droughts of North America: the Civil War drought of 1856–1865, the 1870s drought, the 1890s drought, the great Dust Bowl drought, and the 1950s drought. Seager reported the 1998–2002 period of the recent drought “was most likely caused by multiyear variability of the tropical Pacific Ocean,” noting the recent drought “was the latest in a series of six persistent global hydroclimate regimes, involving a persistent La Niña-like state in the tropical Pacific and dry conditions across the midlatitudes of each hemisphere.”

No aspect of Seager’s study implicated global warming, either CO₂-induced or otherwise, as a cause of or contributor to the turn-of-the-twentieth-century drought that affected large portions of North America. Seager noted, for example, “although the Indian Ocean has steadily warmed over the last half century, this is not implicated as a cause of the turn of the century North American drought because the five prior droughts were associated with cool Indian Ocean sea surface temperatures.” In addition, the five earlier great droughts occurred during periods when the mean global temperature was significantly cooler than what it was during the last great drought.

Woodhouse (2004) covered the western United States, reporting what is known about natural hydroclimatic variability throughout the region. Woodhouse described several major droughts that

occurred there during the past three millennia, all but the last century of which had atmospheric CO₂ concentrations that never varied by more than about 10 ppm from a mean value of 280 ppm.

For comparative purposes, Woodhouse began by noting “the most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts.” The first of these droughts lasted “most of the decade of the 1930s” and “occurred in several waves,” while the latter “also occurred in several waves over the years 1951–1956.” Far more severe than either of these two droughts was the sixteenth century megadrought, which lasted from 1580 to 1600 and included northwestern Mexico in addition to the southwestern United States and the western Great Plains. There was also The Great Drought, which spanned the last quarter of the thirteenth century and was actually the last in a series of three thirteenth-century droughts, the first of which may have been even more severe than the last. In addition, Woodhouse noted there was a period of remarkably sustained drought in the second half of the twelfth century.

According to Woodhouse, “the 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records.” This subset does not even begin to approach the level of drought severity and duration experienced in prior centuries and millennia, which fact was confirmed in a separate paper published by Woodhouse with four coauthors six years later (Woodhouse *et al.*, 2010). It would take a drought much more extreme than the most extreme droughts of the twentieth century to propel the western United States and adjacent portions of Canada and Mexico into a truly unprecedented state of dryness.

Benson *et al.* (2007) reviewed and discussed the possible impacts of early-eleventh, middle-twelfth, and late-thirteenth century droughts on three Native American cultures that occupied parts of the western United States (Anasazi, Fremont, Lovelock) plus another culture that occupied parts of southwestern Illinois (Cahokia). According to the authors, “population declines among the various Native American cultures were documented to have occurred either in the early-11th, middle-12th, or late-13th centuries”—AD 990–1060, 1135–1170, and 1276–1297, respectively—and “really extensive droughts impacted the regions occupied by these prehistoric Native Americans during one or more of these three time periods.” In particular, they found the middle-

twelfth century drought “had the strongest impact on the Anasazi and Mississippian Cahokia cultures,” noting “by AD 1150, the Anasazi had abandoned 85% of their great houses in the Four Corners region and most of their village sites, and the Cahokians had abandoned one or more of their agricultural support centers, including the large Richland farming complex.” In addition, “the sedentary Fremont appear to have abandoned many of their southern area habitation sites in the greater Uinta Basin area by AD 1150 as well as the eastern Great Basin and the Southern Colorado Plateau,” so “in some sense, the 13th century drought may simply have ‘finished off’ some cultures that were already in decline.” Benson *et al.* found these “major reductions in prehistoric Native American habitation sites/population” occurred during a period of “anomalously warm” climatic conditions, which characterized the Medieval Warm Period throughout much of the world at that time.

Two papers by E.R. Cook provide additional information relevant to western United States drought trends. In the first, Cook *et al.* (2004) developed a 1,200-year history of drought for the western half of the country and adjacent parts of Canada and Mexico (hereafter the “West”), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66% of them) possessed data extending back to AD 800. This reconstruction revealed “some remarkable earlier increases in aridity that dwarf the comparatively short-duration current drought in the ‘West.’” Specifically, they reported “the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occur during a ~400 year interval of overall elevated aridity from AD 900 to 1300,” which they observed was “broadly consistent with the Medieval Warm Period.”

Commenting on the strength and severity of Medieval drought, the five scientists reported “the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests that anomalously warm climate conditions during that time may have contributed to the development of more frequent and persistent droughts in the ‘West,’” as well as the megadrought Rein *et al.* (2004) discovered to have occurred in Peru at about the same time (AD 800–1250). After citing nine other studies providing independent evidence of drought during this time period for various sub-regions of the West, Cook *et al.* warned “any trend toward warmer temperatures in the future could lead to a serious

long-term increase in aridity over western North America” and “future droughts in the ‘West’ of similar duration to those seen prior to AD 1300 would be disastrous.”

It is important to note such an unfortunate fate could befall the western United States even in the absence of CO₂-induced global warming, for the millennial-scale oscillation of climate that brought the world the Medieval Warm Period (which was not CO₂-induced) could be repeating itself during the possibly still-ongoing development of the Current Warm Period. In addition, if the association between global warmth and drought in the western United States is indeed robust, current world temperatures must still be far below those experienced during large segments of the Medieval Warm Period, as no drought of Medieval magnitude has accompanied the modern rise in temperature.

In the second of the two papers, Cook *et al.* (2010) wrote “IPCC Assessment Report 4 model projections suggest that the subtropical dry zones of the world will both dry and expand poleward in the future due to greenhouse warming,” and “the US southwest is particularly vulnerable in this regard and model projections indicate a progressive drying there out to the end of the 21st century.” They observed “the USA has been in a state of drought over much of the West for about 10 years now,” and “while severe, this turn of the century drought has not yet clearly exceeded the severity of two exceptional droughts in the 20th century.” As a result, “while the coincidence between the turn of the century drought and projected drying in the Southwest is cause for concern, it is premature to claim that the model projections are correct.”

This fact is understood when the “turn of the century drought” is compared with the two “exceptional droughts” that preceded it by a few decades. Based on gridded instrumental Palmer Drought Severity indices for tree-ring reconstruction extending back to 1900, Cook *et al.* (2010) calculated the turn-of-the-century drought had its greatest Drought Area Index value of 59% in the year 2002, whereas the Great Plains/Southwest drought covered 62% of the United States in its peak year of 1954 and the Dust Bowl drought covered 77% of the nation in 1934. In terms of drought duration, on the other hand, things are not quite as clear. Stahle *et al.* (2007) estimated the first two droughts lasted for 12 and 14 years, respectively; Seager *et al.* (2005) estimated them to have lasted for eight and 10 years; and Andreadis *et al.* (2005) estimated them to have lasted

Observations: Extreme Weather

for seven and eight years. This yields means of nine and 11 years for the two exceptional droughts, compared with 10 or so years for the turn-of-the-century drought, which makes the latter drought not unprecedented even in the twentieth century.

A comparison of the turn-of-the-century drought with droughts of the prior millennium provides clarity on the topic. Cook *et al.* (2010) noted “perhaps the most famous example is the ‘Great Drouth’ (sic) of AD 1276–1299 described by A.E. Douglass (1929, 1935).” This 24-year drought was eclipsed by the 38-year drought found by Weakley (1965) to have occurred in Nebraska from AD 1276 to 1313, which the authors say “may have been a more prolonged northerly extension of the ‘Great Drouth.’” Even these multidecade droughts pale in comparison to the “two extraordinary droughts discovered by Stine (1994) in California that lasted more than two centuries before AD 1112 and more than 140 years before AD 1350.” Each of these megadroughts, as Cook *et al.* (2010) described them, occurred “in the so-called Medieval Warm Period.” And they report “all of this happened *prior to the strong greenhouse gas warming that began with the Industrial Revolution* [emphasis in original].”

Given the above-referenced medieval megadroughts “occurred without any need for enhanced radiative forcing due to anthropogenic greenhouse gas forcing”—because there was none at that time—Cook *et al.* (2010) concluded “there is no guarantee that the response of the climate system to greenhouse gas forcing will result in megadroughts of the kind experienced by North America in the past.” Those who continue to claim global warming will trigger medieval-like megadroughts also must acknowledge the Medieval Warm Period of a thousand years ago had to have been much warmer than the Current Warm Period has been to date.

References

Andreadis, K.M., Clark, E.A., Wood, A.W., Hamlet, A.F., and Lettenmaier, D.P. 2005. Twentieth-century drought in the conterminous United States. *Journal of Hydro-meteorology* **6**: 985–1001.

Benson, L.V., Berry, M.S., Jolie, E.A., Spangler, J.D., Stahle, D.W., and Hattori, E.M. 2007. Possible impacts of early-11th-, middle-12th-, and late-13th-century droughts on western Native Americans and the Mississippian Cahokians. *Quaternary Science Reviews* **26**: 336–350.

Cook, E.R., Seager, R., Heim Jr., R.R., Vose, R.S.,

Herweijer, C., and Woodhouse, C. 2010. Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context. *Journal of Quaternary Science* **25**: 48–61.

Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Douglass, A.E. 1929. The secret of the Southwest solved with talkative tree rings. *National Geographic* **December**: 736–770.

Douglass, A.E. 1935. Dating Pueblo Bonito and other ruins of the Southwest. National Geographic Society Contributed Technical Papers. *Pueblo Bonito Series* **1**: 1–74.

Gray, S.T., Betancourt, J.L., Fastie, C.L., and Jackson, S.T. 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. *Geophysical Research Letters* **30**: 10.1029/2002GL016154.

Mann, M.E., Bradley, R.S., and Hughes, M.K. 1999. Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophysical Research Letters* **26**: 759–762.

Mann, M.E. and Jones, P.D. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**: 10.1029/2003GL017814.

Rein, B., Luckge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

Seager, R. 2007. The turn of the century North American drought: Global context, dynamics, and past analogs. *Journal of Climate* **20**: 5527–5552.

Seager, R., Kushnir, Y., Herweijer, C., Naik, N., and Velez, J. 2005. Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. *Journal of Climate* **18**: 4068–4091.

Stahle, D.W., Fye, F.K., Cook, E.R., and Griffin, R.D. 2007. Tree-ring reconstructed megadroughts over North America since AD 1300. *Climatic Change* **83**: 133–149.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.

Weakly, H.E. 1965. Recurrence of drought in the Great Plains during the last 700 years. *Agricultural Engineering* **46**: 85.

Woodhouse, C.A. 2004. A paleo perspective on hydroclimatic variability in the western United States. *Aquatic Sciences* **66**: 346–356.

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle,

D.W., and Cook, E.R. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences USA* 107: 21,283–21,288.

7.4.4.3.4 Southern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the southern United States.

Writing as background for their study, Chen *et al.* (2012) reported “the IPCC (2007) and the U.S. Climate Report (Karl *et al.*, 2009) predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water,” with the forecast result “it is likely that drought intensity, frequency, and duration will increase in the future for the Southern United States.” To test the validity of this claim, Chen *et al.* used the standard precipitation index (SPI) to characterize drought intensity and duration throughout the Southern United States (SUS) over the past century.

According to the nine researchers, the results indicated there were “no obvious increases in drought duration and intensity during 1895–2007.” Instead, they found “a slight (not significant) decreasing trend in drought intensity.” They noted “although reports from IPCC (2007) and the U.S. Climate Report (Karl *et al.*, 2009) indicated that it is likely that drought intensity, frequency, and duration will increase in the future for the SUS, we did not find this trend in the historical data.” They also noted, although “the IPCC (2007) and U.S. Climate Report predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water,” they “found no obvious increase in air temperature for the entire SUS during 1895–2007.”

References

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., Chappelka, A.H., Prior, S.A., and Lockaby, G.B. 2012. Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. *Climatic Change* 114: 379–397.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis*. Solomon, S., Qin, D., Manniing, M., Chen, Z.,

Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Karl, T.R., Melillo, J.M., and Peterson, T.C. 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press, Cambridge, United Kingdom.

7.4.4.3.5 Entire Conterminous United States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the conterminous United States.

Andreadis and Lettenmaier (2006) examined twentieth-century trends in soil moisture, runoff, and drought over the conterminous United States with a hydroclimatological model forced by real-world measurements of precipitation, air temperature, and wind speed over the period 1915–2003. This work revealed “droughts have, for the most part, become shorter, less frequent, less severe, and cover a smaller portion of the country over the last century.”

Using the self-calibrating Palmer (1965) drought severity index (SCPDSI), as described by Wells *et al.* (2004), Van der Schrier *et al.* (2006) constructed maps of summer moisture availability across a large portion of North America (20–50°N, 130–60°W) for the period 1901–2002 with a spatial latitude/longitude resolution of 0.5° x 0.5°. This revealed for the area as a whole, “the 1930s and 1950s stand out as times of persistent and exceptionally dry conditions, whereas the 1970s and the 1990s were generally wet.” The authors reported “no statistically significant trend was found in the mean summer SCPDSI over the 1901–2002 period, nor in the area percentage with moderate or severe moisture excess or deficit.” Moreover, they could not find a single coherent area within the SCPDSI maps that “showed a statistically significant trend over the 1901–2002 period.”

Fye *et al.* (2003) developed gridded reconstructions of the summer (June–August) basic Palmer Drought Severity Index over the continental United States, based on “annual proxies of drought and wetness provided by 426 climatically sensitive tree-ring chronologies.” This work revealed the greatest twentieth century moisture anomalies across

Observations: Extreme Weather

the United States were the 13-year pluvial in the West in the early part of the century and the epic droughts of the 1930s (the Dust Bowl years) and 1950s, which lasted 12 and 11 years, respectively. Comparing these events to earlier wet and dry periods, they made the following points.

The 13-year pluvial from 1905 to 1917 had three earlier analogs: an extended 16-year pluvial from 1825 to 1840, a prolonged 21-year wet period from 1602 to 1622, and a 10-year pluvial from 1549 to 1558. The 11-year drought from 1946 to 1956, on the other hand, had at least 12 earlier analogs in terms of location, intensity, and duration, but the Dust Bowl drought was greater than all of them—except for a sixteenth century “megadrought” that lasted some 18 years and was, in the words of Fye *et al.*, “the most severe sustained drought to impact North America in the past 500 to perhaps 1000 years.”

Stahle *et al.* (2000) developed a long-term history of North American drought from reconstructions of the Palmer Drought Severity Index based on analyses of many lengthy tree-ring records. This history also showed the 1930s Dust Bowl drought in the United States was eclipsed by the sixteenth century megadrought. This incredible period of dryness, as they described it, persisted “from the 1540s to 1580s in Mexico, from the 1550s to 1590s over the [U.S.] Southwest, and from the 1570s to 1600s over Wyoming and Montana.” In addition, it “extended across most of the continental United States during the 1560s,” and it recurred with greater intensity over the Southeast during the 1580s to 1590s. Stahle *et al.* reported “the ‘megadrought’ of the 16th century far exceeded any drought of the 20th century.” A “precipitation reconstruction for western New Mexico suggests that the 16th-century drought was the most extreme prolonged drought in the past 2000 years.”

Herweijer *et al.* (2006) noted “drought is a recurring major natural hazard that has dogged civilizations through time and remains the ‘world’s costliest natural disaster.’” With respect to the twentieth century, for example, they reported the “major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA.” They also noted “these events are not unique to the twentieth century.” They described three periods of widespread and persistent drought in the latter half of the nineteenth century—1856–1865 (the “Civil War” drought), 1870–1877, and 1890–1896—based on evidence obtained from proxy, historical, and

instrumental data.

With respect to the first of these mid- to late-nineteenth century droughts, Herweijer *et al.* found it “is likely to have had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl drought.” In addition, they reported “drought conditions during the Civil War, 1870s and 1890s droughts were not restricted to the summer months, but existed year round, with a large signal in the winter and spring months.”

The three researchers cited the work of Cook and Krusic (2004), who constructed a North American Drought Atlas using hundreds of tree-ring records. This atlas revealed what Herweijer *et al.* described as “a ‘Mediaeval Megadrought’ that occurred from AD 900 to AD 1300,” along with “an abrupt shift to wetter conditions after AD 1300, coinciding with the ‘Little Ice Age’, a time of globally cooler temperatures” that ultimately gave way to “a return to more drought-prone conditions beginning in the nineteenth century.”

The broad picture emerging from the work of Herweijer *et al.* is one where the most severe North American droughts of the past millennium were associated with the globally warmer temperatures of the Medieval Warm Period plus the initial stage of the globally warmer Current Warm Period. Superimposed upon this low-frequency behavior, Herweijer *et al.* found evidence for a “linkage between a colder eastern equatorial Pacific and persistent North American drought over the last 1000 years,” further noting “Rosby wave propagation from the cooler equatorial Pacific amplifies dry conditions over the USA.” In addition, after using “published coral data for the last millennium to reconstruct a NINO 3.4 history,” they applied “the modern-day relationship between NINO 3.4 and North American drought ... to recreate two of the severest Mediaeval ‘drought epochs’ in the western USA.”

How is it that simultaneous global-scale warmth and regional-scale cold combine to produce the most severe North American droughts? One possible element is variable solar activity, which, as suggested in Chapter 3 of this report, drives the millennial-scale oscillation of climate that produced the global Medieval Warm Period, Little Ice Age, and Current Warm Period. When solar activity is in an ascending mode, the globe as a whole warms, but at the same time, to quote from Herweijer *et al.*’s concluding sentence, increased irradiance typically “corresponds

to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions.”

These observations imply the most severe North American droughts should occur during major multi-centennial global warm periods, as has been observed to be the case. Since the greatest such droughts of the Current Warm Period have not approached the severity of those that occurred during the Medieval Warm Period, one might logically infer the global temperature of the Current Warm Period is not as high as the global temperature that prevailed throughout the Medieval Warm Period.

Stahle *et al.* (2007) used “an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook *et al.*, 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America” since AD 1300. In discussing the Current Warm Period, Stahle *et al.* observed, “the Dust Bowl drought of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America,” citing the studies of Worster (1979), Diaz (1983), and Fye *et al.* (2003). During the Little Ice Age, by contrast, Stahle *et al.* found three megadroughts, which they defined as “very large-scale drought[s] more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle *et al.*, 2000).” They reported “much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine, 1994; Laird *et al.*, 2003; Cook *et al.*, 2004).” These latter megadroughts were so impactful Stahle *et al.* referred to them as “no-analog Medieval megadroughts.”

Herweijer *et al.* (2007) used Palmer Drought Severity Index data found in the North American Drought Atlas prepared by Cook and Krusic (2004), derived from a network of drought-sensitive tree-ring chronologies (some stretching back to AD 800 and encompassing the Medieval Warm Period), placing into a longer perspective “the famous droughts of the instrumental record (i.e., the 1930s Dust Bowl and the 1950s Southwest droughts).” They reported, “the famous droughts of the instrumental era are dwarfed by the successive occurrence of multidecade-long ‘megadroughts’ in the period of elevated aridity between the eleventh and fourteenth centuries AD.” They noted medieval megadroughts, although more

extreme in terms of persistence, “share the severity and spatial distribution characteristics of their modern-day counterparts.” This led them to conclude the mechanism responsible for major North American droughts of the twentieth century “is synonymous with that underlying the megadroughts of the medieval period,” the only difference being the degree of persistence of the forcing that caused them.

What, then, is the common denominator shared by the major North American droughts of the modern and medieval periods?

“With ENSO showing a pronounced signal in the gridded drought reconstructions of the last millennium, both in terms of its link to the leading spatial mode, and the leading time scales of drought variability,” Herweijer *et al.* concluded “medieval megadroughts were forced by protracted La Niña-like tropical Pacific sea surface temperatures.” In addition, they demonstrated “a global hydroclimatic ‘footprint’ of the medieval era revealed by existing paleoclimatic archives from the tropical Pacific and ENSO-sensitive tropical and extratropical land regions.” They observed “this global pattern matches that observed for modern-day persistent North American drought,” namely, “a La Niña-like tropical Pacific.”

A number of paleoclimate studies demonstrate when Earth was significantly warmer than the present, such as during the Medieval Warm Period, ENSO events were often substantially reduced and sometimes even absent (see Chapter 4). Consequently, since the North American droughts of the Medieval Warm Period dwarfed those of the Current Warm Period—with both produced by La Niña-like conditions (which are more prevalent during times of greater warmth)—it follows that the Medieval Warm Period was significantly warmer than the Current Warm Period.

Climate models typically project CO₂-induced global warming will result in more severe droughts. The much more severe and sustained megadroughts of the Little Ice Age appear to render this claim dubious.

Although the severe and sustained no-analogue megadroughts of the Medieval Warm Period would appear to bolster the climate models’ projections, the substantially more severe droughts of that period—if they were indeed related to high global air temperatures—would suggest it is not nearly as warm today as it was during the Medieval Warm Period, when there was far less CO₂ in the air than there is today. These observations undercut the more fundamental claim that the historical rise in the air’s

CO₂ content has been responsible for what the IPCC and others have described as unprecedented twentieth century global warming.

References

- Andreadis, K.M. and Lettenmaier, D.P. 2006. Trends in 20th century drought over the continental United States. *Geophysical Research Letters* **33**: 10.1029/2006GL025711.
- Cook, E.R. and Krusic, P.J. 2004. *North American Summer PDSI Reconstructions*. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2004-045. NOAA/NGDC Paleoclimatology Program.
- Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.
- Diaz, H.F. 1983. Some aspects of major dry and wet periods in the contiguous United States, 1895–1981. *Journal of Climate and Applied Meteorology* **22**: 3–16.
- Fye, F.K., Stahle, D.W., and Cook, E.R. 2003. Paleoclimatic analogs to 20th century moisture regimes across the USA. *Bulletin of the American Meteorological Society* **84**: 901–909.
- Herweijer, C., Seager, R., and Cook, E.R. 2006. North American droughts of the mid to late nineteenth century: a history, simulation and implication for Mediaeval drought. *The Holocene* **16**: 159–171.
- Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J. 2007. North American droughts of the last millennium from a gridded network of tree-ring data. *Journal of Climate* **20**: 1353–1376.
- Laird, K.R., Cumming, B.F., Wunsam, S., Rusak, J.A., Oglesby, R.J., Fritz, S.C., and Leavitt, P.R. 2003. Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proceedings of the National Academy of Sciences USA* **100**: 2483–2488.
- Palmer, W.C. 1965. *Meteorological Drought*. Office of Climatology Research Paper 45. U.S. Weather Bureau, Washington, DC, USA.
- Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell, M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and Luckman, B.H. 2000. Tree-ring data document 16th century megadrought over North America. *EOS, Transactions, American Geophysical Union* **81**: 121, 125.
- Stahle, D.W., Fye, F.K., Cook, E.R., and Griffin, R.D. 2007. Tree-ring reconstructed megadroughts over North America since A.D. 1300. *Climatic Change* **83**: 133–149.
- Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* **369**: 546–549.
- Van der Schrier, G., Briffa, K.R., Osborn, T.J., and Cook, E.R. 2006. Summer moisture availability across North America. *Journal of Geophysical Research* **111**: 10.1029/2005JD006745.
- Wells, N., Goddard, S., and Hayes, M.J. 2004. A self-calibrating Palmer drought severity index. *Journal of Climate* **17**: 2335–2351.
- Worster, D. 1979. *Dust Bowl: The Southern Plains in the 1930s*. Oxford University Press.

7.4.5 Central and South America

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the regions of Central and South America.

Webster *et al.* (2007) removed an active stalagmite (MC01) from the entrance chamber of Macal Chasm—a cave on the Vaca Plateau west of the Rio Macal in the Cavo District of Belize near the border with Guatemala (~17°N, 89°W)—from which they obtained “reliably dated reflectance, color, luminescence, and C and O stable isotope records for the period from 1225 BC to the present.” Upon examination of the record, the authors report the interval “from AD 750 to 1150 was the most prolonged dry phase in our 3300-year record.” This time period corresponds well with the MWP’s mean time of occurrence around the globe, which, Webster *et al.* observed, “coincided with the collapse of the Maya civilization.” They observed their data depicted “a series of droughts centered at about AD 780, 910, 1074, and 1139,” with “successive droughts increasing in severity.”

The seven scientists reported the results of their investigations “add to a growing body of evidence suggesting that severe dryness affected a broad region of Mesoamerica and contributed to the collapse of the Maya civilization during the Late Classic period.” Consequently, although the warmth of the MWP benefited Norse settlers on Greenland, its dryness across a broad swath of Mesoamerica spelled an end to the indigenous civilization of that region.

Morengo (2009) worked with hydro-meteorological indices for the Amazon basin and its several sub-basins “to explore long-term variability of

climate since the late 1920s and the presence of trends and/or cycles in rainfall and river indices in the basin.” These analyses were based on northern and southern Amazonian rainfall data originally developed by Marengo (1992) and Marengo and Hastenrath (1993), and subsequently updated by Marengo (2004). According to the Brazilian researcher, “no systematic unidirectional long-term trends towards drier or wetter conditions [were] identified.” Instead, he found “the rainfall and river series show variability at inter-annual scales.” Of the patterns he uncovered, Morengo observed they are “characteristic of decadal and multi-decadal modes,” which he describes as “indicators of natural climate variability” linked to the El Niño/Southern Oscillation, “rather than any unidirectional trend towards drier conditions (as one would expect, due to increased deforestation or to global warming).”

Minetti *et al.* (2010) evaluated the annual occurrence of droughts and their persistence in what they described as “an attempt to determine any aspects of the impact of global warming.” They examined a regional inventory of monthly droughts for the portion of South America located south of approximately 22°S latitude, dividing the area of study into six sections (the central region of Chile plus five sections making up most of Argentina).

They identified “the presence of long favorable tendencies [1901–2000] regarding precipitations or the inverse of droughts occurrence are confirmed for the eastern Andes Mountains in Argentina with its five sub-regions (Northwest Argentina, Northeast Argentina, Humid Pampa, West-Centre Provinces and Patagonia) and the inverse over the central region of Chile.” From the middle of 2003 to 2009, however, they reported “an upward trend in the occurrence of droughts with a slight moderation over the year 2006.” They additionally noted the driest single-year periods were 1910–1911, 1915–1916, 1916–1917, 1924–1925, and 1933–1934, suggesting twentieth century global warming has not promoted an abnormal increase in droughts in the southern third of South America.

Mundo *et al.* (2012) employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of Argentina’s Neuquen River over the 654-year period AD 1346–2000. According to the eight researchers, in terms of the frequency, intensity, and duration of droughts and pluvial events, “the 20th century contains some of the driest and wettest annual

to decadal-scale events in the last 654 years.” They also noted “longer and more severe events were recorded in previous centuries.” Importantly, the bulk of the 554 years preceding the twentieth century were part of the much colder Little Ice Age, and it would thus appear the global warming of the past century has brought Argentina’s Neuquen River less extreme streamflow conditions.

Masiokas *et al.* (2012) developed the first reconstruction and quantitative analysis of variations in snow accumulation for the past eight-and-a-half centuries in the Andes between 30° and 37°S. The record was based on “instrumental rainfall and streamflow data from adjacent lowlands, a variety of documentary records, and century-long tree-ring series of precipitation-sensitive species from the western side of the Andes,” representing “the first attempt to reconstruct annually-resolved, serially complete snowpack variations spanning most of the past millennium in the Southern Hemisphere.” This record “allows testing the relative severity of recent ‘extreme’ conditions in a substantially longer context.”

The eight researchers report “variations observed in the last 60 years are not particularly anomalous when assessed in a multi-century context,” noting both extreme high and low snowpack values “have not been unusual when assessed in the context of the past eight centuries.” They found “the most extreme dry decades are concentrated between the late 16th century and the mid-18th century,” and there were “decade-long periods of high snowpack levels that equaled or probably surpassed those recorded during the past six decades.”

The results of the several studies described above indicate the warming of the twentieth and early twenty-first centuries has brought nothing unusual, unnatural, or unprecedented in the way of trends in drought frequency and severity for the studied areas of South America.

References

- Marengo, J.A. 1992. Interannual variability of surface climate in the Amazon basin. *International Journal of Climatology* **12**: 853–863.
- Marengo, J.A. 2004. Interdecadal and long term rainfall variability in the Amazon basin. *Theoretical and Applied Climatology* **78**: 79–96.
- Marengo, J.A. 2009. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. *Hydrological Processes* **23**: 3236–3244.

Marengo, J. and Hastenrath, S. 1993. Case studies of extreme climatic events in the Amazon basin. *Journal of Climate* **6**: 617–627.

Masiokas, M.H., Villalba, R., Christie, D.A., Betman, E., Luckman, B.H., Le Quesne, C., Prieto, M.R., and Mauget, S. 2012. Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37°S) inferred from rainfall, tree-ring and documentary records. *Journal of Geophysical Research* **117**: 10.1029/2011JD016748.

Minetti, J.L., Vargas, W.M., Poblete, A.G., de la Zerda, L.R., and Acuña, L.R. 2010. Regional droughts in southern South America. *Theoretical and Applied Climatology* **102**: 403–415.

Mundo, I.A., Masiokas, M.H., Villalba, R., Morales, M.S., Neukom, R., Le Quesne, C., Urrutia, R.B., and Lara, A. 2012. Multi-century tree-ring based reconstruction of the Neuquen River streamflow, northern Patagonia, Argentina. *Climate of the Past* **8**: 815–829.

Webster, J.W., Brook, G.A., Railsback, L.B., Cheng, H., Edwards, R.L., Alexander, C., and Reeder, P.P. 2007. Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya collapse. *Palaeogeography, Palaeoclimatology, Palaeoecology* **250**: 1–17.

7.4.6 Global

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the entire planet.

Svensson *et al.* (2005) examined twentieth century river flow data for a group of 21 stations distributed around the globe, which they obtained from the Global Runoff Data Centre in Koblenz, Germany. Individual record lengths for the 21 stations varied from 44 to 100 years, with an average of 68 years, and the three researchers' analyses of the data consisted of computing trends in both high flows and low flows using Mann-Kendall and linear regression methods. In the case of high flows, their work revealed slightly more stations exhibiting significant negative trends (reduced flooding) than significant positive trends (increased flooding). With respect to low flows, nearly all stations showed increasing trends, approximately half of which were significant at the 90% level, indicative of a general trend of decreasing drought throughout the world.

Huntington (2006) reviewed the current state of

science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and a number of other water-related parameters. He found on a globally averaged basis, “precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998).” He also reported “an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987),” and a reanalysis of those trends for the period 1920–1995 “confirmed an increase in world continental runoff during the 20th century (Labat *et al.*, 2004).” Huntington further reported “summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al.*, 2000).”

Narisma *et al.* (2007) analyzed “global historical rainfall observations to detect regions that have undergone large, sudden decreases in rainfall [that] are statistically significant at the 99% level, are persistent for at least ten years, and ... have magnitudes that are [mostly] 10% lower than the climatological normal (1901–2000 rainfall average).” Working with the gridded high-resolution (0.5 x 0.5 degrees of latitude and longitude) global precipitation dataset of Mitchell *et al.* (2004), which covers the period 1901–2000, they identified 30 drought episodes throughout the world that satisfied these stringent criteria during the twentieth century. These episodes included the sudden and prolonged Sahel drought of Africa in the late 1960s; the United States Dust Bowl of the 1930s and Southwest drought of the 1950s (which also affected parts of Mexico); the strong and persistent droughts that occurred in northeast China in the 1920s, in Kazakhstan and regions of the former Soviet Union in the late 1930s, in southeast Australia in the late 1930s, and in southern Africa and eastern Europe in the 1980s; the World War II droughts of 1937–1945; and the droughts that occurred over large regions of East India and Bangladesh in the 1950s.

Seven of the 30 severe and persistent droughts identified by Narisma *et al.* occurred during the first two decades of the twentieth century (1901–1920), seven occurred during the next two decades (1921–1940), eight during the middle two decades of the century (1941–1960), only five during the next two decades (1961–1980), and a mere three during the final two decades of the century (1981–2000). This distribution is not at all what one would have expected if the model-based thesis propounded by the

IPCC were correct.

The scientists who performed the analysis reported the 30 major droughts they identified were “mostly located in semi-arid and arid regions” that “are naturally prone to large fluctuations.” The 30 major droughts of the twentieth century were therefore likely natural in all respects and hence “indicative of what could also happen in the future,” as Narisma *et al.* state in their concluding paragraph.

Sheffield and Wood (2008) studied “variability and trends in soil moisture and drought characteristics, globally and regionally over the second half of the twentieth century.” They used “a global soil moisture dataset derived from a model simulation of the terrestrial hydrologic cycle,” which was “driven by a hybrid observation-reanalysis-based meteorological dataset.” This work revealed “an overall increasing trend in global soil moisture, driven by increasing precipitation, underlies the whole analysis, which is reflected most obviously over the western hemisphere and especially in North America.” In addition, they determined “trends in drought characteristics are predominantly decreasing” and “concurrent changes in drought spatial extent are evident, with a global decreasing trend of -0.021% to -0.035% per year.” They also discovered “a switch in later years to a drying trend, globally and in many regions,” which they say was “concurrent with increasing temperatures.” This drying trend was not strong enough to overpower the increasing trend of global soil moisture over the entire half-century of their analysis.

In a subsequent analysis of the same time period, Sheffield *et al.* (2009) used “observation-driven simulations of global terrestrial hydrology and a cluster algorithm that searches for spatially connected regions of soil moisture” to identify “296 large scale drought events (greater than 500,000 km² and longer than 3 months) globally for 1950–2000.” They reported “the mid-1950s showed the highest drought activity and the mid-1970s to mid-1980s the lowest activity.”

References

- Dai, A., Fung, I.Y., and DelGenio, A.D. 1997. Surface observed global land precipitation variations during 1900–1998. *Journal of Climate* **10**: 2943–2962.
- Hulme, M., Osborn, T.J., and Johns, T.C. 1998. Precipitation sensitivity to global warming: comparisons of observations with HadCM2 simulations. *Geophysical Research Letters* **25**: 3379–3382.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* **319**: 83–95.

Labat, D., Godderis, Y., Probst, J.L., and Guyot, J.L. 2004. Evidence for global runoff increase related to climate warming. *Advances in Water Resources* **27**: 631–642.

Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M., and New, M. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall Center Working Paper 55, Norwich, UK.

Narisma, G.T., Foley, J.A., Licker, R., and Ramankutty, N. 2007. Abrupt changes in rainfall during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028628.

Probst, J.L. and Tardy, Y. 1987. Long range streamflow and world continental runoff fluctuations since the beginning of this century. *Journal of Hydrology* **94**: 289–311.

Robock, A., Konstantin, Y.V., Srinivasan, J.K., Entin, J.K., Hollinger, N.A., Speranskaya, N.A., Liu, S., and Nampkai, A. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* **81**: 1281–1299.

Sheffield, J., Andreadis, K.M., Wood, E.F., and Lettenmaier, D.P. 2009. Global and continental drought in the second half of the twentieth century: severity-area-duration analysis and temporal variability of large-scale events. *Journal of Climate* **22**: 1962–1981.

Sheffield, J. and Wood, E.F. 2008. Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate* **21**: 432–458.

Svensson, C., Kundzewicz, Z.W., and Maurer, T. 2005. Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrological Sciences Journal* **50**: 811–824.

7.5 Floods

Climate model simulations generally predict a future with more frequent and more severe floods in response to CO₂-induced global warming. Confirming such predictions has remained an elusive task, according to the IPCC, which claims in its most recent report “there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale” (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

Contrary to the IPCC’s assessment of the

situation, there exists a large body of scientific research on this topic. According to that research, as outlined in the subsections that follow, there is much evidence to conclude CO₂-induced global warming is not currently increasing the frequency and/or magnitude of floods, nor will it likely impact such phenomena in the future.

7.5.1 Africa

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Africa.

Noting “droughts and floods represent extreme conditions, and are precisely those that are foreseen to increase in [the] future with global change,” Heine (2004) analyzed soil sequences and slackwater deposits laid down over the course of the Holocene in valleys of the Namibian Desert, located between southern Angola and South Africa along the South Atlantic Ocean and stretching inland about 200 km, where it abuts on Africa’s Great Western Escarpment. The author reports “during the Holocene, slackwater deposits of the Namib Desert valleys accumulated between ca. 10 and 8 ka BP and between ca. 2 and 0 ka BP.” Of the latter period, he notes “the youngest accumulation phase occurred during the Little Ice Age (LIA, ca. AD 1300 to 1850).” In addition, he finds “the biggest flash floods of the LIA, in most catchments, experienced water levels in the valleys that exceeded the most extreme floods of the last 100 to 150 years.”

Commenting on the nature of the LIA itself, Heine reports “maximum LIA cooling occurred around AD 1700 (ca. -1°C),” noting “this cold period was coeval with cool events recorded in a large variety of proxy data from all sites over southern Africa and from corals in the ocean off southwestern Madagascar (Tyson *et al.*, 2001).”

In Africa’s Namib Desert, the greatest floods of the past two millennia occurred during its coldest period, the Little Ice Age, with nothing to compare to them during what the IPCC typically describes as the warmest portion of the past two millennia; i.e., the latter part of the twentieth century.

References

Heine, K. 2004. Flood reconstructions in the Namib Desert, Namibia and Little Ice Age climatic implications: Evidence

from slackwater deposits and desert soil sequences. *Journal of the Geological Society of India* **64**: 535–547.

Tyson, P.D., Odada, E.O., and Partridge, T.C. 2001. Late-Quaternary and Holocene environmental change in Southern Africa. *South African Journal of Science* **97**: 139–149.

7.5.2 Asia

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Asia.

Cluis and Laberge (2001) analyzed the flow records of 78 rivers distributed throughout the entire Asia-Pacific region to see if there had been any enhancement of Earth’s hydrologic cycle coupled with an increase in variability that might have led to more floods between the mean beginning and end dates of the flow records: 1936 ± 5 years and 1988 ± 1 year, respectively. The two scientists determined mean river discharges were unchanged over this period in 67% of the cases investigated; where they found trends, 69% of them were downward. In addition, maximum river discharges were unchanged in 77% of the cases investigated; where there were trends, 72% of them were downward. Contrary to model-based claims of global warming leading to more frequent and more severe flooding, the two researchers observed no changes in these flood characteristics in the majority of the rivers they studied; and where there were changes, more of them were of the type that typically leads to less flooding and less severe floods.

Kale *et al.* (2003) conducted geomorphic studies of slackwater deposits in the bedrock gorges of the Tapi and Narmada Rivers of central India, assembling long chronologies of large floods of these rivers. They found “since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837.” With respect to large floods on the Narmada River, they reported at least nine or ten floods between the beginning of the Christian era and AD 400; between AD 400 and 1000 they documented six or seven floods, between 1000 and 1400 about eight or nine floods, and after 1950 three more such floods. On the basis of texture, elevation, and thickness of the flood units, they conclude “the periods AD 400–1000 and post-1950 represent periods of extreme floods.”

What do these findings imply about the effects of global warming on central India flood events? The post-1950 period is often claimed by the IPCC to have been the warmest of the past millennium, and it has indeed experienced some extreme floods. However, the flood characteristics of the AD 400–1000 period are described in equivalent terms, and this was a rather cold climatic interval known as the Dark Ages Cold Period (see, for example, McDermott *et al.* (2001) and Andersson *et al.* (2003)). In addition, the most extreme flood in the much shorter record of the Tapi River occurred in 1837, near the beginning of one of the colder periods of the Little Ice Age. There appears to be little correlation between the flood characteristics of the Tapi and Narmada Rivers of central India and the thermal state of the global climate.

Touchan *et al.* (2003) developed two reconstructions of spring (May–June) precipitation from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia*, and *Pinus nigra*, and the other (1339–1998) based on three chronologies of *Juniperus excelsa*. The authors report these reconstructions “show clear evidence of multi-year to decadal variations in spring precipitation,” with both wet and dry periods of 1–2 years duration being well distributed throughout the record. In the case of more extreme hydrologic events, they found all of the wettest 5-year periods preceded the industrial revolution, manifesting themselves at times when the air’s carbon dioxide content was largely unaffected by anthropogenic CO₂ emissions.

In a study of the Upper Volga and Zapadnaya Dvina Rivers, Panin and Nefedov (2010) documented “the geomorphological and altitudinal positions of [human] occupational layers corresponding to 1224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province,” identifying “a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchical rank.” The two researchers report finding “low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs,” because “during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in

seasonal peaks in lake levels.” They note “a model of past warming epochs can be the warming in the late 20th century, still continuing now.” They also report finding, “in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays.” In addition, their results indicate the period AD 1000–1300 hosted the greatest number of floodplain occupations of the period studied.

Panin and Nefedov state this last period and other “epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th–early current century,” which they say “is forming under the effect of directed climate change.” This relationship clearly implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

Davi *et al.* (2006) developed a reconstruction of streamflow that extended from 1637 to 1997, based on absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia, all of which sites were in or near the Selenge River basin, the largest river in Mongolia. Of the ten wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the ten extreme periods, respectively), once again indicative of a propensity for less flooding during the warmest portion of the 360-year period.

Jiang *et al.* (2005) analyzed pertinent historical documents to produce a 1,000-year time series of flood and drought occurrence in the Yangtze Delta of Eastern China (30 to 33°N, 119 to 122°E), whose nearly level plain averages only two to seven meters above sea level across 75% of its area and is vulnerable to flooding and maritime tidal hazards. They found alternating wet and dry episodes occurred throughout the 1,000-year period, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850).

Zhang *et al.* (2007) also developed flood and drought histories of the Yangtze Delta for the past thousand years, “from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports.” They then applied “continuous wavelet transform ... to detect the periodicity and variability of the flood/drought series.” The results were compared with 1,000-year

Observations: Extreme Weather

temperature histories of northeastern Tibet and southern Tibet. This work revealed, in the words of the researchers, that “colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region.” They state, “during AD 1400–1700 [the coldest portion of their record, corresponding to much of the Little Ice Age], the proxy indicators showing the annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred.” In contrast, they report “during AD 1000–1400 [the warmest portion of their record, corresponding to much of the Medieval Warm Period], relatively stable changes of climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region.”

Zhang *et al.* (2009) utilized wavelet analysis on the decadal locust abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al.* (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al.* (2002) for the AD 950s–1950s, “to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China.” The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events. The six scientists state “global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China,” noting these findings “challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects.” They say their results are an example of “benign effects of global warming on the regional risk of natural disasters.”

Zha *et al.* (2012) conducted a paleohydrological field investigation in the central portion of the Jinghe River, the middle and upper reaches of which are located in a semiarid zone with a monsoonal climate, between Binxian county and Chunhua county of Shaanxi Province. Their analysis revealed five extraordinary palaeoflood events determined to have occurred between 4100 and 4000 years BP; these floods “corresponded exactly with palaeoflood events (4200–4000 yr BP) recorded in the middle reaches of

Qishuie River,” demonstrating “extraordinary flood events were common during the episode of 4200–4000 yr BP in the middle reaches of the Yellow River.”

The four Chinese researchers note “during the mid-Holocene climatic optimum, global climate was warm-humid and the climate system was stable,” and during this time, they say, “there were no flood records identified in the middle reaches of the Yellow river,” citing the work of Huang *et al.* (2011a,b). Thereafter, however, they report “global climatic cooling events occurred at about 4200 years BP, which was also well recorded by various climatic proxies in China,” citing Zhang *et al.* (2004). In addition, they write “the decline of the Neolithic Longshan Culture in the period around 4000 years BP was thought to be linked with the global cooling events,” as suggested by the work of Wu *et al.* (2001, 2004, 2005).” These observations led them to conclude, “the extraordinary floods recorded in the middle reaches of the Jinghe River were linked to the global climatic events”—all of which were global cooling events..

In a study focusing on the headwater region of the Sushui River within the Yuncheng Basin in the southeast part of the middle reaches of China’s Yellow River, Huang *et al.* (2007) constructed a complete catalog of Holocene overbank flooding events at a watershed scale, based on pedo-sedimentary records of the region’s semiarid piedmont alluvial plains, including the color, texture, and structure of the sediment profiles, along with determinations of particle-size distributions, magnetic susceptibilities, and elemental concentrations. This work revealed six major episodes of overbank flooding. The first occurred at the onset of the Holocene, the second immediately before the mid-Holocene Climatic Optimum, and the third in the late stage of the mid-Holocene Climatic Optimum. The last three episodes coincided with “the cold-dry stages during the late Holocene.” Speaking of the last of the overbank flooding episodes, they note it “corresponds with the well documented ‘Little Ice Age,’” when “climate departed from its long-term average conditions and was unstable, irregular, and disastrous,” which is pretty much how the Little Ice Age has been described in many other parts of the world as well.

The findings of these several Asian-based studies provide no support for the claim that global warming leads to more frequent and severe flooding. If anything, they tend to suggest just the opposite.

References

- Andersson, C., Risebrobakken, B., Jansen, E., and Dahl, S.O. 2003. Late Holocene surface ocean conditions of the Norwegian Sea (Voring Plateau). *Paleoceanography* **18**: 10.1029/2001PA000654.
- Cluis, D. and Laberge, C. 2001. Climate change and trend detection in selected rivers within the Asia-Pacific region. *Water International* **26**: 411–424.
- Davi, N.K., Jacoby, G.C., Curtis, A.E., and Baatarbileg, N. 2006. Extension of drought records for central Asia using tree rings: West-Central Mongolia. *Journal of Climate* **19**: 288–299.
- Gong, G.-C., Liu, K.-K., Chiang, K.-P., Hsiung, T.-M., Chang, J., Chen, C.-C., Hung, C.-C., Chou, W.-C., Chung, C.-C., Chen, H.-Y., Shiah, F.K., Tsai, A.-Y., Hsieh, C.-h., Shiao, J.-C., Tseng, C.-M., Hsu, S.-C., Lee, H.-J., Lee, M.-A., Lin, I.-I., and Tsai, F. 2011. Yangtze River floods enhance coastal ocean phytoplankton biomass and potential fish production. *Geophysical Research Letters* **38**: 10.1029/2011GL047519.
- Huang, C., Pang, J., Zha, X., Su, H., and Jia, Y. 2011a. Extraordinary floods related to the climatic event at 4200 a BP on the Qishuihe River, middle reaches of the Yellow River, China. *Quaternary Science Reviews* **30**: 460–468.
- Huang, C., Pang, J., Zha, X., Zhou, Y., Su, H., Wan, H., and Ge, B. 2011b. Sedimentary records of extraordinary floods at the ending of the mid-Holocene climatic optimum along the Upper Weihe River, China. *The Holocene* 10.1177/0959683611409781.
- Huang, C.C., Pang, J., Zha, X., Su, H., Jia, Y., and Zhu, Y. 2007. Impact of monsoonal climatic change on Holocene overbank flooding along Sushui River, middle reach of the Yellow River, China. *Quaternary Science Reviews* **26**: 2247–2264.
- Jiang, T., Zhang, Q., Blender, R., and Fraedrich, K. 2005. Yangtze Delta floods and droughts of the last millennium: Abrupt changes and long term memory. *Theoretical and Applied Climatology* **82**: 131–141.
- Kale, V.S., Mishra, S., and Baker, V.R. 2003. Sedimentary records of palaeofloods in the bedrock gorges of the Tapi and Narmada rivers, central India. *Current Science* **84**: 1072–1079.
- Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.
- Ma, S. 1958. The population dynamics of the oriental migratory locust (*Locusta migratoria manilensis* Meyen) in China. *Acta Entomologica Sinica* **8**: 1–40.
- McDermott, F., Matthey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem $\delta^{18}\text{O}$ record from SW Ireland. *Science* **294**: 1328–1331.
- Panin, A.V. and Nefedov, V.S. 2010. Analysis of variations in the regime of rivers and lakes in the Upper Volga and Upper Zapadnaya Dvina based on archaeological-geomorphological data. *Water Resources* **37**: 16–32.
- Touchan, R., Garfin, G.M., Meko, D.M., Funkhouser, G., Erkan, N., Hughes, M.K., and Wallin, B.S. 2003. Preliminary reconstructions of spring precipitation in southwestern Turkey from tree-ring width. *International Journal of Climatology* **23**: 157–171.
- Wu, W. and Ge, Q. 2005. The possibility of occurring of the extraordinary floods on the eve of establishment of the Xia Dynasty and the historical truth of Dayu's successful regulating of floodwaters. *Quaternary Sciences* **25**: 741–749.
- Wu, W. and Liu, T. 2001. 4000 a BP event and its implications for the origin of ancient Chinese civilization. *Quaternary Sciences* **21**: 443–451.
- Wu, W. and Liu, T. 2004. Variations in East Asian monsoon around 4000 a BP and the collapse of Neolithic cultures around Central Plain. *Quaternary Sciences* **24**: 278–284.
- Yang, B., Brauning, A., Johnson, K.R., and Yafeng, S. 2002. Temperature variation in China during the last two millennia. *Geophysical Research Letters* **29**: 10.1029/2001GL014485.
- Zha, X., Huang, C., Pang, J., and Li, Y. 2012. Sedimentary and hydrological studies of the Holocene palaeofloods in the middle reaches of the Jinghe River. *Journal of Geographical Sciences* **22**: 470–478.
- Zhang, Z., Cazelles, B., Tian, H., Stige, L.C., Brauning, A., and Stenseth, N.C. 2009. Periodic temperature-associated drought/flood drives locust plagues in China. *Proceedings of the Royal Society B* **276**: 823–831.
- Zhang, Q., Chen, J., and Becker, S. 2007. Flood/drought change of last millennium in the Yangtze Delta and its possible connections with Tibetan climatic changes. *Global and Planetary Change* **57**: 213–221.
- Zhang, Q., Yang, D., Shi, Y., Ge, Z.-S., and Jiang, T. 2004. Flood events since 5000 a BP recorded in natural sediments of Zhongba Site, Chuanjiang River. *Scientia Geographica Sinica* **24**: 715–720.

7.5.3 Europe

7.5.3.1 France

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to France.

On September 8 and 9, 2002, extreme flooding of the Gardon River in southern France occurred as approximately half an average year's rainfall was received in approximately 20 hours. This flooding claimed the lives of several people and caused much damage to towns and villages situated adjacent to the river's channel. The event elicited much coverage in the press, and in the words of Sheffer *et al.* (2003a), "this flood is now considered by the media and professionals to be 'the largest flood on record,'" which record extends back to 1890.

Coincidentally, Sheffer *et al.* were in the midst of a study of prior floods of the Gardon River when the "big one" hit, and they had data spanning a much longer time period against which to compare its magnitude. Based on that data as presented in their paper, they report "the extraordinary flood of September 2002 was not the largest by any means," noting "similar, and even larger floods have occurred several times in the recent past," with three of the five greatest floods they identified to that point in time occurring over the period AD 1400–1800 during the Little Ice Age. Sheffer *et al.* state, "using a longer time scale than human collective memory, paleoflood studies can put in perspective the occurrences of the extreme floods that hit Europe and other parts of the world during the summer of 2002." That perspective clearly shows even greater floods occurred repeatedly during the Little Ice Age, the coldest period of the current interglacial.

Sheffer *et al.* (2008) analyzed geomorphic, sedimentologic, and hydrologic data associated with both historical and late Holocene floods from two caves and two alcoves of a 1,600-meter-long stretch of the Gardon River, which they hoped would provide a longer and better-defined perspective on the subject. They discovered "at least five floods of a larger magnitude than the 2002 flood occurred over the last 500 years," all of which took place, as they describe it, "during the Little Ice Age." In addition, they note "the Little Ice Age has been related to increased flood frequency in France (Guilbert, 1994; Coeur, 2003;

Sheffer, 2003; Sheffer *et al.*, 2003a,b; Sheffer, 2005), and in Spain (Benito *et al.*, 1996; Barriendos and Martin Vide, 1998; Benito *et al.*, 2003; Thorndycraft and Benito, 2006a,b)."

Renard *et al.* (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high-flow and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations having a minimum record length of 40 years. They determined "at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive." At the smaller scale of hydroclimatic regions, they also discovered no significant results for most areas.

Wilhelm *et al.* (2012) note "mountain-river floods triggered by extreme precipitation events can cause substantial human and economic losses (Gaume *et al.*, 2009)," and they state "global warming is expected to lead to an increase in the frequency and/or intensity of such events (IPCC, 2007), especially in the Mediterranean region (Giorgi and Lionello, 2008)." They point out "reconstructions of geological records of intense events are an essential tool for extending documentary records beyond existing observational data and thereby building a better understanding of how local and regional flood hazard patterns evolve in response to changes in climate."

Wilhelm *et al.* analyzed the sediments of Lake Allos, a 1-km-long by 700-m-wide high-altitude lake in the French Alps (44°14'N, 6°42'35'E), by means of both seismic survey and lake-bed coring, carrying out numerous grain size, geochemical, and pollen analyses of the sediment cores they obtained in conjunction with a temporal context derived using several radionuclide dating techniques. The 13 French researchers report their investigations revealed the presence of 160 graded sediment layers over the last 1,400 years, and comparisons of the most recent of these layers with records of historic floods suggest the sediment layers are indeed representative of significant floods that were "the result of intense meso-scale precipitation events." Of special interest is their finding of "a low flood frequency during the Medieval Warm Period and more frequent and more intense events during the Little Ice Age," which meshes nicely with the results of an analysis of a Spanish lake sediment archive that allowed Moreno *et al.* (2008) to infer "intense precipitation events occurred more frequently during the Little Ice Age

than they did during the Medieval Warm Period.”

Wilhelm *et al.* additionally state “the Medieval Warm Period was marked by very low hydrological activity in large rivers such as the Rhone (Arnaud *et al.*, 2005; Debret *et al.*, 2010), the Moyenne Durance (Miramont *et al.*, 1998), and the Tagus (Benito *et al.*, 2003), and in mountain streams such as the Taravilla lake inlet (Moreno *et al.*, 2008).” Of the Little Ice Age, they write, “research has shown higher flood activity in large rivers in southern Europe, notably in France (Miramont *et al.*, 1998; Arnaud *et al.*, 2005; Debret *et al.*, 2010), Italy (Belotti *et al.*, 2004; Giraudi, 2005) and Spain (Benito *et al.*, 2003), and in smaller catchments (e.g., in Spain, Moreno *et al.*, 2008).”

Wilhelm *et al.* conclude their study shows “sediment sequences from high altitude lakes can provide reliable records of flood-frequency and intensity-patterns related to extreme precipitation events,” warning “such information is required to determine the possible impact of the current phase of global warming.”

Pirazzoli (2000) analyzed tide-gauge and meteorological data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions and strong surge winds in this region “are becoming less frequent.” The data also revealed “ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding.”

References

- Arnaud, F., Revel, M., Chapron, E., Desmet, M., and Tribovillard, N. 2005. 7200 years of Rhone river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology. *The Holocene* **15**: 420–428.
- Barriendos, M. and Martin Vide, J. 1998. Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal area (14th–19th centuries). *Climatic Change* **38**: 473–491.
- Belotti, P., Caputo, C., Davoli, L., Evangelista, S., Garzanti, E., Pugliese, F., and Valeri, P. 2004. Morpho-sedimentary characteristics and Holocene evolution of the emergent part of the Ombrone River delta (southern Tuscany). *Geomorphology* **61**: 71–90.
- Benito, G., Diez-Herrero, A., and de Villalta, M. 2003. Magnitude and frequency of flooding in the Tagus river (Central Spain) over the last millennium. *Climatic Change* **58**: 171–192.
- Benito, G., Machado, M.J., and Perez-Gonzalez, A. 1996. Climate change and flood sensitivity in Spain. *Geological Society Special Publication* **115**: 85–98.
- Coeur, D. 2003. Genesis of a public policy for flood management in France: the case of the Grenoble valley (XVIIIth–XIXth Centuries). In: Thorndycraft, V.R., Benito, G., Barriendos, M. and Llasat, M.C. (Eds.) *Palaeofloods, Historical Floods and Climatic Variability: Applications in Flood Risk Assessment*. CSIC, Madrid, Spain, pp. 373–378.
- Debret, M., Chapron, E., Desmet, M., Rolland-Revel, M., Magand, O., Trentesaux, A., Bout-Roumazielle, V., Nomade, J., and Arnaud, F. 2010. North western Alps Holocene paleohydrology recorded by flooding activity in Lake Le Bourget, France. *Quaternary Science Reviews* **29**: 2185–2200.
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., Blaskovicova, L., Blochl, G., Borgia, M., Dumitrescu, A., Daliakopoulos, I., Garcia, J., Irimescu, A., Kohnova, S., Koutroulis, A., Marchi, L., Matreata, S., Medina, V., Preciso, E., Sempere-Torres, D., Stancalie, G., Szolgay, J., Tsanis, I., Velasco, D., and Viglione, A. 2009. A compilation of data on European flash floods. *Journal of Hydrology* **367**: 70–78.
- Giorgi, F. and Lionello, P. 2008. Climate change projections for the Mediterranean region. *Global and Planetary Change* **63**: 90–104.
- Giraudi, C. 2005. Late-Holocene alluvial events in the Central Apennines, Italy. *The Holocene* **15**: 768–773.
- Guilbert, X. 1994. Les crues de la Durance depuis le XIVeme siècle. Frequence, periodicite et interpretation paleo-climatique. *Memoire de maitrise de Geographie*. Universite d’Aix-Marseille I, Aix-en-Provence.
- IPCC. 2007. *Climate Change 2007—The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom.
- Miramont, C., Jorda, M., and Pichard, G. 1998. Evolution historique de la morphogenese et de la dynamique fluviale d’une riviere mediterraneenne: l’exemple de la moyenne Durance (France du sud-est). *Geographie physique et Quatenaire* **52**: 381–392.
- Moreno, A., Valero-Garces, B., Gonzales-Samperiz, P., and Rico, M. 2008. Flood response to rainfall variability during the last 2000 years inferred from the Taravilla Lake record (Central Iberian Range, Spain). *Journal of Paleolimnology* **40**: 943–961.
- Pirazzoli, P.A. 2000. Surges, atmospheric pressure and wind change and flooding probability on the Atlantic coast of France. *Oceanologica Acta* **23**: 643–661.
- Renard, B., Lang, M., Bois, P., Dupeyrat, A., Mestre, O., Niel, H., Sauquet, E., Prudhomme, C., Parey, S., Paquet,

E., Neppel, L., and Gailhard, J. 2008. Regional methods for trend detection: Assessing field significance and regional consistency. *Water Resources Research* **44**: 10.1029/2007WR006268.

Sheffer, N.A. 2003. Paleoflood Hydrology of the Ardeche River, France. A Contribution to Flood Risk Assessment. M.Sc. Dissertation, The Hebrew University of Jerusalem, Israel.

Sheffer, N.A. 2005. Reconstructing the paleoclimate record using paleoflood hydrology as a proxy. *Fifth Conference on Active Research, CARESS 2005*. The Weizmann Institute of Science, Rehovot, Israel.

Sheffer, N.A., Enzel, Y., Benito, G., Grodek, T., Porat, N., Lang, M., Naulet, R., and Coeur, D. 2003b. Paleofloods and historical floods of the Ardeche River, France. *Water Resources Research* **39**: 1376.

Sheffer, N.A., Enzel, Y., Grodek, T., Waldmann, N., and Benito, G. 2003a. Claim of largest flood on record proves false. *EOS: Transactions, American Geophysical Union* **84**: 109.

Sheffer, N.A., Rico, M., Enzel, Y., Benito, G., and Grodek, T. 2008. The palaeoflood record of the Gardon River, France: A comparison with the extreme 2002 flood event. *Geomorphology* **98**: 71–83.

Thorndycraft, V.R. and Benito, G. 2006a. Late Holocene fluvial chronology of Spain: the role of climatic variability and human impact. *Catena* **66**: 34–41.

Thorndycraft, V.R. and Benito, G. 2006b. The Holocene fluvial chronology of Spain: evidence from a newly compiled radiocarbon database. *Quaternary Science Reviews* **25**: 223–234.

Wilhelm, B., Arnaud, F., Sabatier, P., Crouzet, C., Brisset, E., Chaumillon, E., Disnar, J.-R., Guiter, F., Malet, E., Reyss, J.-L., Tachikawa, K., Bard, E., and Delannoy, J.-J. 2012. 1400 years of extreme precipitation patterns over the Mediterranean French Alps and possible forcing mechanisms. *Quaternary Research* **78**: 1–12.

7.5.3.2 Germany

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Germany.

Burger *et al.* (2007) reviewed what is known about flooding in southwest Germany over the past three centuries. According to the six scientists, the

extreme flood of the Neckar River in October 1824 was “the largest flood during the last 300 years in most parts of the Neckar catchment.” They further note “it was the highest flood ever recorded in most parts of the Neckar catchment and also affected the Upper Rhine, the Mosel and Saar.” They report the historical floods of 1845 and 1882 “were among the most extreme floods in the Rhine catchment in the 19th century,” which they describe as “catastrophic events.” The flood of 1845 “showed a particular impact in the Middle and Lower Rhine and in this region it was higher than the flood of 1824.” Two extreme floods occurred in 1882, one at the end of November and another at the end of December. Of the first one, Burger *et al.* say “in Koblenz, where the Mosel flows into the Rhine, the flood of November 1882 was the fourth-highest of the recorded floods, after 1784, 1651 and 1920,” with the much-hyped late-twentieth century floods of 1993, 1995, 1998, and 2002 not even meriting a mention.

Czymzik *et al.* (2010) write “assumptions about an increase in extreme flood events due to an intensified hydrological cycle caused by global warming are still under discussion and must be better verified,” while noting some historical flood records indicate “flood frequencies were higher during colder periods (Knox, 1993; Glaser and Stangl, 2004), challenging the hypothesis of a correlation between the frequency of extreme floods and a warmer climate.”

In June 2007 Czymzik *et al.* retrieved two sediment cores from the deepest part of Lake Ammersee in southern Germany (48°00'N, 11°07'E), which is fed primarily by the River Ammer. They analyzed the cores using what they describe as “a novel methodological approach that combines microfacies analyses, high-resolution element scanning (μ -XRF), stable isotope data from bulk carbonate samples ($\delta^{13}\text{C}_{\text{carb}}$, $\delta^{18}\text{O}_{\text{carb}}$), and X-ray diffraction (XRD) analyses (Brauer *et al.*, 2009).” The six scientists determined the flood frequency distribution over the 450-year time series “is not stationary but reveals maxima for colder periods of the Little Ice Age when solar activity was reduced.” They report “similar observations have been made in historical flood time series of the River Main, located approximately 200 km north of Ammersee (Glaser and Stangl, 2004), pointing to a wider regional significance of this finding.”

Bormann *et al.* (2011) write, “following several severe floods in Germany during the past two decades, [the] mass media as well as scientists have

debated the relative contributions of climate and/or anthropogenic processes to those floods.” The three researchers utilized long time-series of stage and discharge data obtained from 78 river gauges in Germany, searching for trends in flood frequency, peak discharge, peak stage, and stage-discharge relationships, where all variables investigated had to have a temporal history of at least half a century.

They first established the nature of Germany’s temperature history, noting Schonwiese (1999) identified a homogenous positive trend of 0.5–1.0°C over the course of the twentieth century, which was subsequently confirmed by Gerstengarbe and Werner (2008) and Bormann (2010). Then, in terms of land use change between 1951 and 1989, they report “agricultural area in Germany decreased from 57.8% to 53.7%, while forested areas remained almost constant.” During this period, they report, “impervious areas increased sharply from 7.4% to 12.3%,” and they state “this trend has continued since 1989,” with impervious areas further increasing from 11.2% to 13.1%, forest areas increasing from 29.3% to 30.1%, and agricultural area decreasing from 54.7% to 52.5%. As a consequence of the net increase in impervious surfaces, they note, “runoff generation can be expected to increase and infiltration and groundwater recharge decrease,” which would be expected to lead to increases in river flow and a potential for more frequent and extreme floods. However, they report “most stations analyzed on the German rivers did not show statistically significant trends in any of the metrics analyzed.”

In light of these observations—plus the fact that “most decadal-scale climate-change impacts on flooding (Petrow and Merz, 2009) are small compared to historic peaks in flood occurrence (Mudelsee *et al.*, 2006)”—Bormann *et al.* conclude these facts “should be emphasized in the recent discussion on the effect of climate change on flooding.” The warming experienced in Germany over the past century has not led to unprecedented flooding; in fact, it has not led to any increase in flooding.

References

- Bormann, H. 2010. Changing runoff regimes of German rivers due to climate change. *Erdkunde* **64**: 257–279.
- Bormann, H., Pinter, N., and Elfert, S. 2011. Hydrological signatures of flood trends on German rivers: Flood frequencies, flood heights and specific stages. *Journal of Hydrology* **404**: 50–66.
- Brauer, A., Dulski, P., Mangili, C., Mingram, J., and Liu, J. 2009. The potential of varves in high-resolution paleolimnological studies. *PAGESnews* **17**: 96–98.
- Burger, K., Seidel, J., Glasser, R., Sudhaus, D., Dostal, P., and Mayer, H. 2007. Extreme floods of the 19th century in southwest Germany. *La Houille Blanche*: 10.1051/lhb:2007008.
- Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., and Brauer, A. 2010. A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 10.1029/2009WR008360.
- Gerstengarbe, F.-W. and Werner, P.C. 2008. Climate development in the last century—global and regional. *International Journal of Medical Microbiology* **298**: 5–11.
- Glaser, R. and Stangl, H. 2004. Climate and floods in Central Europe since AD 1000: Data, methods, results and consequences. *Surveys in Geophysics* **25**: 485–510.
- Knox, J.C. 1993. Large increases in flood magnitude in response to modest changes in climate. *Nature* **361**: 430–432.
- Mudelsee, M., Deutsch, M., Borngen, M., and Tetzlaff, G. 2006. Trends in flood risk of the river Werra (Germany) over the past 500 years. *Hydrological Sciences Journal* **51**: 818–833.
- Petrow, T. and Merz, B. 2009. Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. *Journal of Hydrology* **371**: 129–141.
- Schonwiese, C.-D. 1999. Das Klima der jüngeren Vergangenheit. *Physik in unserer Zeit* **30**: 94–101.

7.5.3.3 United Kingdom

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to the United Kingdom.

Reynard *et al.* (2001) used a continuous flow simulation model to assess the impacts of potential climate and land use changes on flood regimes of the UK’s Thames and Severn Rivers. As is typical of a model study, it predicted modest increases in the magnitudes of 50-year floods on these rivers when the climate was forced to change as predicted for various global warming scenarios. However, when the modelers allowed forest cover to rise concomitantly,

they found this land use change “acts in the opposite direction to the climate changes and under some scenarios is large enough to fully compensate for the shifts due to climate.”

To better determine what might actually happen in the real world, therefore, it is important to consider how the forested areas of the rivers’ catchments might change in the future. Two things come into play here. First, if forests are deemed to be important carbon sinks for which countries may get sequestration credits, and if nations begin to employ them as such, the UK government may promote the development of new forests on much of the land in question. Second, as the air’s CO₂ content continues to rise, there will be a great natural impetus for forests to expand their ranges and grow in areas where grasses now dominate the landscape. Consequently, forests may expand on the river catchments and neutralize any predicted increases in flood activity in a future high-CO₂ world.

Macklin *et al.* (2005) developed what they described as “the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ¹⁴C-dated British flood deposits.” They compared their reconstructed flood history “with high-resolution proxy-climate records from the North Atlantic region, northwest Europe and the British Isles to critically test the link between climate change and flooding.” They determined “the majority of the largest and most widespread recorded floods in Great Britain [had] occurred during cool, moist periods,” and “comparison of the British Holocene palaeoflood series ... with climate reconstructions from tree-ring patterns of subfossil bog oaks in northwest Europe also suggests that a similar relationship between climate and flooding in Great Britain existed during the Holocene, with floods being more frequent and larger during relatively cold, wet periods.” In addition, they state “an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ¹⁴C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods.”

Noting “recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments,” and that “projections suggest that flooding may increase in [the] future as a result of human-induced warming,” Hannaford and Marsh (2008) used the UK “benchmark network” of 87 “near-natural catchments” identified by Bradford and Marsh (2003) to

conduct “a UK-wide appraisal of trends in high-flow regimes unaffected by human disturbances.” They report “significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK.” However, they say “there is little compelling evidence for high-flow trends in lowland areas in the south and east.” They also found “in western areas, high-flow indicators are correlated with the North Atlantic Oscillation Index (NAOI),” so “recent trends may therefore reflect an influence of multi-decadal variability related to the NAOI.” In addition, they state longer river flow records from five additional catchments they studied “provide little compelling evidence for long-term (>50 year) trends but show evidence of pronounced multi-decadal fluctuations.”

Hannaford and Marsh also found “in comparison with other indicators, there were fewer trends in flood magnitude” and “trends in peaks-over-threshold frequency and extended-duration maxima at a gauging station were not necessarily associated with increasing annual maximum instantaneous flow.” They conclude “considerable caution should be exercised in extrapolating from any future increases in runoff or high-flow frequency to an increasing vulnerability to extreme flood events.”

References

- Bradford, R.B. and Marsh, T.M. 2003. Defining a network of benchmark catchments for the UK. *Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering* **156**: 109–116.
- Hannaford, J. and Marsh, T.J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology* **28**: 1325–1338.
- Macklin, M.G., Johnstone, E., and Lewin, J. 2005. Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *The Holocene* **15**: 937–943.
- Reynard, N.S., Prudhomme, C., and Crooks, S.M. 2001. The flood characteristics of large UK rivers: Potential effects of changing climate and land use. *Climatic Change* **48**: 343–359.

7.5.3.4 Spain

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced

global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Spain.

“Starting from historical document sources, early instrumental data (basically, rainfall and surface pressure) and the most recent meteorological information,” Llasat *et al.* (2005) analyzed “the temporal evolution of floods in NE Spain since the 14th century,” focusing on the river Segre in Lleida, the river Llobregat in El Prat, and the river Ter in Girona. They found “an increase of flood events for the periods 1580–1620, 1760–1800 and 1830–1870,” and they report “these periods are coherent with chronologies of maximum advance in several alpine glaciers.” In addition, calculations from their tabulated data for the aggregate of the three river basins show the mean number of what Llasat *et al.* call catastrophic floods per century for the fourteenth through nineteenth centuries was 3.55 ± 0.22 , while the corresponding number for the twentieth century was only 1.33 ± 0.33 .

The four Spanish researchers conclude, “we may assert that, having analyzed responses inherent to the Little Ice Age and due to the low occurrence of frequent flood events or events of exceptional magnitude in the 20th century, the latter did not present an excessively problematic scenario.” Having introduced their paper with descriptions of the devastating effects of the September 1962 flash flood in Catalonia (more than 800 deaths), the August 1996 flash flood in the Spanish Pyrenees (87 deaths), and the floods of September 1992 that produced much loss of life and material damage in France and Italy, they hastened to add the more recent “damage suffered and a perception of increasing vulnerability is something very much alive in public opinion and in economic balance sheets.”

Benito *et al.* (2010) reconstructed flood frequencies of the Upper Guadalentin River in southeast Spain using “geomorphological evidence, combined with one-dimensional hydraulic modeling and supported by records from documentary sources at Lorca in the lower Guadalentin catchment.” The combined palaeoflood and documentary records indicate past floods were clustered during particular time periods: AD 950–1200 (10), AD 1648–1672 (10), AD 1769–1802 (9), AD 1830–1840 (6), and AD 1877–1900 (10), where the first time interval coincides with the Medieval Warm Period and the latter four fall within the confines of the Little Ice Age. By calculating mean rates of flood occurrence

over each of the five intervals, a value of 0.40 floods per decade during the Medieval Warm Period and an average value of 4.31 floods per decade over the four parts of the Little Ice Age can be determined. The latter value is more than ten times greater than the mean flood frequency experienced during the Medieval Warm Period.

Barredo *et al.* (2012) say “economic impacts from flood disasters have been increasing over recent decades,” adding, “despite the fact that the underlying causes of such increase are often attributed to a changing climate, scientific evidence points to increasing exposure and vulnerability as the main factors responsible for the increase in losses,” citing the studies of Pielke and Landsea (1998), Crompton and McAneney (2008), Pielke *et al.* (2008), Barredo (2009, 2010), and Neumayer and Barthel (2011). Barredo *et al.* examined “the time history of insured losses from floods in Spain between 1971 and 2008,” striving to see “whether any discernible residual signal remains after adjusting the data for the increase in the number and value of insured assets over this period of time.”

The “most salient feature” of Barredo *et al.*’s findings, as they describe it, is “the absence of a significant positive trend in the adjusted insured flood losses in Spain,” suggesting “the increasing trend in the original losses is explained by socio-economic factors, such as the increases in exposed insured properties, value of exposed assets and insurance penetration.” They add “there is no residual signal that remains after adjusting for these factors,” so “the analysis rules out a discernible influence of anthropogenic climate change on insured losses,” which they say “is consistent with the lack of a positive trend in hydrologic floods in Spain in the last 40 years.”

References

- Barredo, J.I. 2009. Normalized flood losses in Europe: 1970–2006. *Natural Hazards and Earth System Sciences* **9**: 97–104.
- Barredo, J.I. 2010. No upward trend in normalized windstorm losses in Europe: 1970–2008. *Natural Hazards and Earth System Sciences* **10**: 97–104.
- Barredo, J.I., Sauri, D., and Llasat, M.C. 2012. Assessing trends in insured losses from floods in Spain 1971–2008. *Natural Hazards and Earth System Sciences* **12**: 1723–1729.
- Benito, G., Rico, M., Sanchez-Moya, Y., Sopena, A.,

Thorndycraft, V.R., and Barriendos, M. 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentin River, southeast Spain. *Global and Planetary Change* **70**: 53–63.

Crompton, R.P. and McAneney, K.J. 2008. Normalized Australian insured losses from meteorological hazards: 1967–2006. *Environmental Science and Policy* **11**: 371–378.

Llasat, M.-C., Barriendos, M., Barrera, A., and Rigo, T. 2005. Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records. *Journal of Hydrology* **313**: 32–47.

Neumayer, E. and Barthel, F. 2011. Normalizing economic loss from natural disasters: A global analysis. *Global Environmental Change* **21**: 13–24.

Pielke Jr., R.A., Gratz, J., Landsea, C.W., Collins, D., Saunders, M.A., and Musulin, R. 2008. Normalized hurricane damage in the United States: 1900–2005. *Natural Hazards Review* **31**: 29–42.

Pielke Jr., R.A. and Landsea, C.W. 1998. Normalized hurricane damage in the United States: 1925–95. *Weather and Forecasting* **13**: 621–631.

7.5.3.5 Switzerland

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Switzerland.

Schmocker-Fackel and Naef (2010a) investigated how flooding in Switzerland may have responded to the post-Little Ice Age warming of the past century and a half, especially in light of the extreme flooding that occurred there in 1999, 2005, and 2007. They “analyzed streamflow data from 83 stations with a record length of up to 105 years, complemented with data from historical floods dating back to 1850.” The two researchers found, “in Switzerland, periods with frequent floods have alternated with quieter periods during the last 150 years,” and “since 1900, flood-rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa.” They also note although “three of the four largest large-scale flood events in northern Switzerland have all occurred within the last ten years,” “a similar accumulation of large floods has already been observed in the second half of the 19th century,” and

“studies about changes in precipitation frequencies in Switzerland come to similar conclusions,” citing the work of Bader and Bantle (2004).

In a contemporaneous publication, Schmocker-Fackel and Naef (2010b) collected and analyzed historical flood data from 14 catchments in northern Switzerland. This second work revealed four periods of frequent flooding lasting between 30 and 100 years each: 1560–1590, 1740–1790, 1820–1940, and since 1970. Schmocker-Fackel and Naef report the first three periods of intervening low flood frequency (1500–1560, 1590–1740, and 1790–1810) were found to correspond to periods of low solar activity. However, they note, “after 1810 no relationship between solar activity and flood frequency was found, nor could a relationship be established between reconstructed North Atlantic Oscillation indices or reconstructed Swiss temperatures.” In addition, they determined “the current period of increased flood frequencies has not yet exceeded those observed in the past.” They also note “a comparison with the flood patterns of other European rivers suggests that flood frequencies are not in phase over Europe.”

Schmocker-Fackel and Naef conclude “the current period with more floods in northern Switzerland, which started in the mid 1970s, might continue for some decades,” even under conditions of “natural climatic variation.”

Stewart *et al.* (2011) note “regional climate models project that future climate warming in Central Europe will bring more intense summer-autumn heavy precipitation and floods as the atmospheric concentration of water vapor increases and cyclones intensify,” citing the studies of Arnell and Liu (2001), Christensen and Christensen (2003), and Kundzewicz *et al.* (2005). They derived “a complete record of paleofloods, regional glacier length changes (and associated climate phases) and regional glacier advances and retreats (and associated climate transitions) ... from the varved sediments of Lake Silvaplana (ca. 1450 BC–AD 420; Upper Engadine, Switzerland),” while indicating “these records provide insight into the behavior of floods (i.e. frequency) under a wide range of climate conditions.”

The five researchers report there was “an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June–July–August temperatures” and the frequency of flooding “was reduced during warm and/or dry climates.” Reiterating that “the findings of this study suggest that the frequency of extreme summer–autumn precipitation events (i.e. flood events) and the

associated atmospheric pattern in the Eastern Swiss Alps was not enhanced during warmer (or drier) periods,” Stewart *et al.* acknowledge “evidence could not be found that summer–autumn floods would increase in the Eastern Swiss Alps in a warmer climate of the 21st century,” in contrast to the projections of regional climate models that have suggested otherwise.

References

Arnell, N. and Liu, C. 2001. Hydrology and water resources. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (Eds.) *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.

Bader, S. and Bantle, H. 2004. Das schweizer klima im trend, Temperatur—und Niederschlagsentwicklung 1864–2001. Veröffentlichung der MeteoSchweiz Nr. 68.

Christensen, J.H. and Christensen, O.B. 2003. Climate modeling: severe summertime flooding in Europe. *Nature* **421**: 805–806.

Kundzewicz, Z.W., Ulbrich, U., Brucher, T., Graczyk, D., Kruger, A., Leckebusch, G.C., Menzel, L., Pinskiwar, I., Radziejewski, M., and Szwed, M. 2005. Summer floods in Central Europe—climate change track? *Natural Hazards* **36**: 165–189.

Schmocker-Fackel, P. and Naef, F. 2010b. Changes in flood frequencies in Switzerland since 1500. *Hydrology and Earth System Sciences* **14**: 1581–1594.

Schmocker-Fackel, P. and Naef, F. 2010a. More frequent flooding? Changes in flood frequency in Switzerland since 1850. *Journal of Hydrology* **381**: 1–8.

Stewart, M.M., Grosjean, M., Kuglitsch, F.G., Nussbaumer, S.U., and von Gunten, L. 2011. Reconstructions of late Holocene paleofloods and glacier length changes in the Upper Engadine, Switzerland (ca. 1450 BC–AD 420). *Palaeogeography, Palaeoclimatology, Palaeoecology* **311**: 215–223.

7.5.3.6 Multiple Countries

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to multiple countries across Europe.

Starkel (2002) reviewed what is known about the relationship between extreme weather events and the thermal climate of Europe during the Holocene. This review clearly demonstrated more extreme fluvial activity was typically associated with *cooler* time intervals. In recovering from one such period (the Younger Dryas), for example, temperatures in Germany and Switzerland rose by 3–5°C over several decades; “this fast shift,” in Starkel’s words, “caused a rapid expansion of forest communities, [a] rise in the upper treeline and higher density of vegetation cover,” which led to a “drastic” reduction in sediment delivery from slopes to river channels.

Mudelsee *et al.* (2003) analyzed historical documents from the eleventh century to 1850, plus subsequent water stage and daily runoff records from then until 2002, for two of the largest rivers in central Europe: the Elbe and Oder Rivers. For the prior 80 to 150 years, which the IPCC typically describes as a period of unprecedented global warming, they discovered “a decrease in winter flood occurrence in both rivers, while summer floods show[ed] no trend, consistent with trends in extreme precipitation occurrence.”

Mudelsee *et al.* (2004) wrote “extreme river floods have had devastating effects in central Europe in recent years,” citing as examples the Elbe flood of August 2002, which caused 36 deaths and inflicted damages totaling more than US \$15 billion, and the Oder flood of July 1997, which caused 114 deaths and inflicted approximately US \$5 billion in damages. They note concern had been expressed “in the Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change,” wherein it was stated “current anthropogenic changes in atmospheric composition will add to this risk.”

The four researchers reevaluated the quality of data and methods of reconstruction that had previously produced flood histories of the middle parts of the Elbe and Oder rivers back to AD 1021 and 1269, respectively. For both rivers, they found “no significant trends in summer flood risk in the twentieth century,” but “significant downward trends in winter flood risk.” The latter phenomenon—described as “a reduced winter flood risk during the instrumental period”—they specifically described as “a response to regional warming.” Thus their study provided no support for the IPCC’s concern that CO₂-induced warming would add to the risk of river flooding in Europe. If anything, their findings suggest just the opposite.

Based on flood loss information obtained from the Emergency Events Database and Natural Hazards Assessment Network, Barredo (2009) developed a 1970–2006 history of normalized monetary flood losses in Europe—including the member states of the European Union along with Norway, Switzerland, Croatia, and the former Yugoslav Republic of Macedonia—by calculating the value of losses that would have occurred if the floods of the past had taken place under the current socioeconomic conditions of the continent, while further removing inter-country price differences by adjusting the losses for purchasing power parities. This work revealed, in the analyst’s words, “no evidence of a clear positive trend in normalized flood losses in Europe,” and “changes in population, inflation and per capita real wealth are the main factors contributing to the increase of the original raw losses.” After removing the influence of socioeconomic factors, the European Commission researcher states, “there remains no evident signal suggesting any influence of anthropogenic climate change on the trend of flood losses in Europe during the assessed period.”

Buntgen *et al.* (2010) point out instrumental station measurements, which systematically cover only the past 100–150 years, “hinder any proper assessment of the statistical likelihood of return period, duration and magnitude of climatic extremes,” stating “a palaeoclimatic perspective is therefore indispensable to place modern trends and events in a pre-industrial context (Battipaglia *et al.*, 2010), to disentangle effects of human greenhouse gas emission from natural forcing and internal oscillation (Hegerl *et al.*, 2011), and to constrain climate model simulations and feedbacks of the global carbon cycle back in time (Frank *et al.*, 2010).” Buntgen *et al.* “introduce and analyze 11,873 annually resolved and absolutely dated ring width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period,” and which “allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations.”

The nine researchers state their data revealed “a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming.” This finding, the authors write, “may question the common belief that frequency and severity of such events closely relates to climate mean states.”

References

- Barredo, J.I. 2009. Normalized flood losses in Europe: 1970–2006. *Natural Hazards and Earth System Sciences* **9**: 97–104.
- Battipaglia, G., Frank, D.C., Buntgen, U., Dobrovolsky, P., Brazdil, R., Pfister, C., and Esper, J. 2010. Five centuries of Central European temperature extremes reconstructed from tree-ring density and documentary evidence. *Global and Planetary Change* **72**: 182–191.
- Buntgen, U., Brazdil, R., Heussner, K.-U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chroma, K., and Tegel, W. 2011. Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium. *Quaternary Science Reviews* **30**: 3947–3959.
- Frank, D.C., Esper, J., Raible, C.C., Buntgen, U., Trouet, V., Joos, F., and Stocker, B. 2010. Ensemble reconstruction constraints of the global carbon cycle sensitivity to climate. *Nature* **463**: 527–530.
- Hegerl, G., Luterbacher, J., Gonzalez-Rouco, F.J., Tett, S., Crowley, T., and Xoplaki, E. 2011. Influence of human and natural forcing on European seasonal temperatures. *Nature Geosciences* **4**: 99–103.
- Mudelsee, M., Borngen, M., Tetzlaff, G., and Grunewald, U. 2003. No upward trends in the occurrence of extreme floods in central Europe. *Nature* **425**: 166–169.
- Mudelsee, M., Borngen, M., Tetzlaff, G., and Grunewald, U. 2004. Extreme floods in central Europe over the past 500 years: Role of cyclone pathway “Zugstrasse Vb.” *Journal of Geophysical Research* **109**: 10.1029/2004JD005034.
- Starkel, L. 2002. Change in the frequency of extreme events as the indicator of climatic change in the Holocene (in fluvial systems). *Quaternary International* **91**: 25–32.
- 7.5.3.7 Other European Countries**
- As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to other countries in Europe not previously discussed in prior subsections of this topic.
- 7.5.3.7.1 Norway**
- Nesje *et al.* (2001) analyzed a sediment core from a lake in southern Norway in an attempt to determine

the frequency and magnitude of prior floods in that region. The last thousand years of the record revealed “a period of little flood activity around the Medieval period (AD 1000–1400),” followed by a period of extensive flood activity associated with the “post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the ‘Little Ice Age.’” Thus this study suggests the post-Little Ice Age warming Earth has experienced for the last century or two—which could continue for some time to come—should be leading this portion of the planet into a period of less extensive flooding as opposed to the more extensive flooding typically predicted by climate models to occur in response to warming.

7.5.3.7.2 Finland

According to Korhonen and Kuusisto (2010), “annual mean temperatures in Finland increased by about 0.7°C during the 20th century,” citing Jylha *et al.* (2004), while noting under such a warming regime, “both droughts and floods are expected to intensify.” The two Finnish researchers analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland to 2004, using data supplied by the Finnish Environment Institute.

They found as “winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites.” They further noted “the magnitudes of spring high flow have not changed.” Low flows, by contrast, “have increased at about half of the unregulated sites due to an increase in both winter and summer discharges.” They conclude, “statistically significant overall changes have not been observed in mean annual discharge.” Thus, in contrast to typical global warming projections, at the high end where flooding may occur, there has been no change in the magnitude of flows. At the low end, where droughts may occur, there has been an increase in flow magnitude, which acts to prevent or leads to less frequent and/or less severe episodes of drought.

7.5.3.7.3 Slovakia

Stankoviansky (2003) employed topographical maps and aerial photographs, field geomorphic investigation, and the study of historical documents, including those from local municipal and church

sources, to determine the spatial distribution of gully landforms and the temporal history of their creation in the Myjava Hill Land of Slovakia, situated in the western part of the country near its border with the Czech Republic. He found “the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s and the second roughly between the 1780s and 1840s.” He determined these gullies were formed “during periods of extensive forest clearance and expansion of farmland,” but “the triggering mechanism of gullying was extreme rainfalls during the Little Ice Age.” He notes “the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age.” Subsequently, from the mid-nineteenth century to the present, he reports “there has been a decrease in gully growth because of the afforestation of gullies and especially climatic improvements since the termination of the Little Ice Age.”

7.5.3.7.4 Sweden

Lindstrom and Bergstrom (2004) analyzed runoff and flood data from more than 60 discharge stations throughout Sweden, some of which provided information stretching as far back in time as the early 1800s, when Sweden and the world were still experiencing the cold of the Little Ice Age. They discovered the last 20 years of the past century were indeed unusually wet, with a runoff anomaly of +8% compared with the century average. But they also found “the runoff in the 1920s was comparable to that of the two latest decades,” and “the few observation series available from the 1800s show that the runoff was even higher than recently.” In addition, they determined “flood peaks in old data [were] probably underestimated,” which “makes it difficult to conclude that there has really been a significant increase in average flood levels.” They also state “no increased frequency of floods with a return period of 10 years or more, could be determined.”

Lindstrom and Bergstrom conclude conditions in Sweden “are consistent with results reported from nearby countries: e.g. Forland *et al.* (2000), Bering Ovesen *et al.* (2000), Klavins *et al.* (2002) and Hyvarinen (2003),” and “in general, it has been difficult to show any convincing evidence of an

increasing magnitude of floods (e.g. Roald, 1999) in the near region, as is the case in other parts of the world (e.g. Robson *et al.*, 1998; Lins and Slack, 1999; Douglas *et al.*, 2000; McCabe and Wolock, 2002; Zhang *et al.*, 2001).”

7.5.3.7.5 Poland

Cyberski *et al.* (2006) used documentary sources of information (written documents and “flood boards”) to develop a reconstruction of winter flooding of the Vistula River in Poland back to AD 988. This work indicated, in their words, that winter floods “have exhibited a decreasing frequency of snowmelt and ice-jam floods in the warming climate over much of the Vistula basin.” In addition, they report the work of Pfister (2005) indicates most of Central Europe also has become less drought-prone in winter during the twentieth century. It would appear twentieth century global warming has been accompanied by reductions in floods and droughts in much of Central Europe, just the opposite of model-based projections.

7.5.3.7.6 Italy

Diodato *et al.* (2008) undertook a detailed analysis of “the Calore River Basin (South Italy) erosive rainfall using data from 425-year-long series of both observations (1922–2004) and proxy-based reconstructions (1580–1921).” This work revealed pronounced interdecadal variations, “with multi-decadal erosivity reflecting the mixed population of thermo-convective and cyclonic rainstorms with large anomalies,” and they note “the so-called Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall.”

The three researchers conclude, “in recent years, climate change (generally assumed as synonymous with global warming) has become a global concern and is widely reported in the media.” With respect to the concern that both droughts and floods will become both more frequent and more severe as the planet warms, they say their study indicates “climate in the Calore River Basin has been largely characterized by naturally occurring weather anomalies in past centuries (long before industrial CO₂ emissions), not only in recent years,” and there has been a “relevant smoothing” of such events during the modern era.

References

- Bering Ovesen, N., Legard Iversen, H., Larsen, S., Muller-Wohlfeil, D.I., and Svendsen, L. 2000. *Afstromningsforhold i Danske Vandlob*. Faglig rapport fra DMU, no. 340. Miljo-og Energiministeriet. Danmarks Miljoundersogelser, Silkeborg, Denmark.
- Cyberski, J., Grzes, M., Gutry-Korycka, M., Nachlik, E., and Kundzewicz, Z.W. 2006. History of floods on the River Vistula. *Journal des Sciences Hydrologiques* **51**: 799–817.
- Diodato, N., Ceccarelli, M., and Bellocchi, G. 2008. Decadal and century-long changes in the reconstruction of erosive rainfall anomalies in a Mediterranean fluvial basin. *Earth Surface Processes and Landforms* **33**: 2078–2093.
- Douglas, E.M., Vogel, R.M., and Kroll, C.N. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* **240**: 90–105.
- Forland, E., Roald, L.A., Tveito, O.E., and Hanssen-Bauer, I. 2000. *Past and Future Variations in Climate and Runoff in Norway*. DNMI Report no. 1900/00 KLIMA, Oslo, Norway.
- Hyvarinen, V. 2003. Trends and characteristics of hydrological time series in Finland. *Nordic Hydrology* **34**: 71–90.
- Jylha, K., Tuomenvirta, H., and Ruosteenoja, K. 2004. Climate change projections in Finland during the 21st century. *Boreal Environmental Research* **9**: 127–152.
- Klavins, M., Briede, A., Rodinov, V., Kokorite, I., and Frisk, T. 2002. Long-term changes of the river runoff in Latvia. *Boreal Environmental Research* **7**: 447–456.
- Korhonen, J. and Kuusisto, E. 2010. Long-term changes in the discharge regime in Finland. *Hydrology Research* **41**: 253–268.
- Lindstrom, G. and Bergstrom, S. 2004. Runoff trends in Sweden 1807–2002. *Hydrological Sciences Journal* **49**: 69–83.
- Lins, H.F. and Slack, J.R. 1999. Streamflow trends in the United States. *Geophysical Research Letters* **26**: 227–230.
- McCabe, G.J. and Wolock, D.M. 2002. A step increase in streamflow in the conterminous United States. *Geophysical Research Letters* **29**: 2185–2188.
- Nesje, A., Dahl, S.O., Matthews, J.A., and Berrisford, M.S. 2001. A ~4500-yr record of river floods obtained from a sediment core in Lake Atnsjoen, eastern Norway. *Journal of Paleolimnology* **25**: 329–342.
- Pfister, C. 2005. Weeping in the snow. The second period of Little Ice Age-type impacts, 1570–1630. In: Behringer,

W., Lehmann, H. and Pfister, C. (Eds.) *Kulturelle Konsequenzen der "Kleinen Eiszeit,"* Vandenhoeck, Gottingen, Germany, pp. 31–86.

Roald, L.A. 1999. *Analyse av Lange Flomserier.* HYDRA-rapport no. F01, NVE, Oslo, Norway.

Robson, A.J., Jones, T.K., Reed, D.W., and Bayliss, A.C. 1998. A study of national trends and variation in UK floods. *International Journal of Climatology* **18**: 165–182.

Stankoviansky, M. 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. *Catena* **51**: 223–239.

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. 2001. Trends in Canadian streamflow. *Water Resources Research* **37**: 987–998.

7.5.4 North America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to North America.

Lins and Slack (1999) analyzed secular streamflow trends in 395 parts of the United States derived from more than 1,500 individual stream gauges, some of which had continuous data stretching back to 1914. In the mean, they found “the conterminous U.S. is getting wetter, but less extreme.” That is to say, as the near-surface air temperature of the planet gradually rose throughout the twentieth century, the United States became wetter in the mean but less variable at the extremes, which is where floods and droughts occur, leading to what could be considered the best of both worlds: more water with fewer floods.

Molnar and Ramirez (2001) conducted a detailed analysis of precipitation and streamflow trends for the period 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. At the annual timescale, they reported finding “a statistically significant increasing trend in precipitation,” driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale, but monthly totals increased in low-flow months and decreased in high-flow months, once again reducing the likelihood of both floods and droughts.

Increased precipitation in a semiarid region would seem to be a good thing. Having most of the increase arrive in the moderate rainfall intensity range also would appear to be a good thing. Increasing streamflow in normally low-flow months sounds good too, as does decreasing streamflow in high-flow months. The changes in precipitation and streamflow observed by Molnar and Ramirez would appear to be highly desirable, leading to more water availability but a lowered probability of both floods and droughts.

Knox (2001) identified an analogous phenomenon in the more mesic Upper Mississippi River Valley. Since the 1940s and early 1950s, the magnitudes of the largest daily flows in this much wetter region have been decreasing while the magnitude of the average daily baseflow has been increasing, once again manifesting simultaneous trends towards both lessened flood and drought conditions.

Garbrecht and Rossel (2002) studied the nature of precipitation throughout the U.S. Great Plains over the period 1895–1999. For the central and southern Great Plains, the last two decades of this period were found to be the longest and wettest of the 105 years of record, due primarily to a reduction in the number of dry years and an increase in the number of wet years. Once again, however, the number of very wet years, which would be expected to produce flooding, “did not increase as much and even showed a decrease for many regions.”

The northern and northwestern Great Plains experienced a precipitation increase near the end of Garbrecht and Rossel’s 105-year record, but the increase was confined primarily to the final decade of the twentieth century. As they report, “fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions.”

The last decade of the past century did produce significant floods, such as the 1997 flooding of the Red River of the North, which devastated Grand Forks, North Dakota as well as parts of Canada. As Haque (2000) reports, this flood was the largest in the Red River over the past century, but it was not the largest in historic times. In 1852, for example, there was a slightly larger Red River flood, and in 1826 there was a flood nearly 40% greater than that of 1997. The temperature of the globe was much colder at the times of these earlier catastrophic floods than it was in 1997, suggesting one cannot attribute the strength of the 1997 flood to the degree of warmth experienced that year or the preceding decade.

Observations: Extreme Weather

Olsen *et al.* (1999) report some upward trends in flood-flows have been found in certain places along the Mississippi and Missouri Rivers; there will always be exceptions to the general rule. At the same time, they note many of the observed upward trends were highly dependent upon the length of the data record and when the trends began and ended. Hence, they say these trends “were not necessarily there in the past and they may not be there tomorrow.”

Pinter *et al.* (2008) also tested for long-term changes in flood magnitudes and frequencies in the Mississippi River system. They “constructed a hydrologic database consisting of data from 26 rated stations (with both stage and discharge measurements) and 40 stage-only stations.” Then, to help “quantify changes in flood levels at each station in response to construction of wing dikes, bendway weirs, meander cutoffs, navigational dams, bridges, and other modifications,” the researchers compiled a geospatial database consisting of “the locations, emplacement dates, and physical characteristics of over 15,000 structural features constructed along the study rivers over the past 100–150 years.” Pinter *et al.* say “significant climate- and/or land use-driven increases in flow were detected,” but “the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures, followed by progressive levee construction.”

Pinter *et al.* write “the navigable rivers of the Mississippi system have been intensively engineered, and some of these modifications are associated with large decreases in the rivers’ capacity to convey flood flows.” It would appear man may indeed have been responsible for most of the enhanced flooding of the rivers of the Mississippi system over the past century or so, but not in the way suggested by the IPCC. The question that needs addressing by the region’s inhabitants, therefore, has nothing to do with CO₂, but everything to do with how to “balance the local benefits of river engineering against the potential for large-scale flood magnification.”

Similar findings have been reported for the Upper Midwest (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois) by Villarini *et al.* (2011), who “analyzed the annual maximum instantaneous flood peak distributions for 196 U.S. Geological Survey stream-flow stations with a record of at least 75 years over the Midwest U.S.” According to the four U.S. researchers, the majority of streamflow changes they observed were “associated with change-points (both

in mean and variance) rather than monotonic trends,” and they indicated “these non-stationarities are often associated with anthropogenic effects.” But rather than associate the increases with anthropogenic CO₂ emissions, they cite such things as “changes in land use/land cover, changes in agricultural practice, and construction of dams and reservoirs” as the primary cause(s). “In agreement with previous studies (Olsen *et al.*, 1999; Villarini *et al.*, 2009),” they conclude “there is little indication that anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S.” And as they make doubly clear in the abstract of their paper, “trend analyses do not suggest an increase in the flood peak distribution due to anthropogenic climate change.”

Villarini and Smith (2010) “examined the distribution of flood peaks for the eastern United States using annual maximum flood peak records from 572 U.S. Geological Survey stream gaging stations with at least 75 years of observations.” This work revealed, “in general, the largest flood magnitudes are concentrated in the mountainous central Appalachians and the smallest flood peaks are concentrated along the low-gradient Coastal Plain and in the northeastern United States.” They also found “landfalling tropical cyclones play an important role in the mixture of flood generating mechanisms, with the frequency of tropical cyclone floods exhibiting large spatial heterogeneity over the region.” They also note “warm season thunderstorm systems during the peak of the warm season and winter-spring extratropical systems contribute in complex fashion to the spatial mixture of flood frequency over the eastern United States.”

Of even greater interest to the climate change debate, they found “only a small fraction of stations exhibited significant linear trends,” and “for those stations with trends, there was a split between increasing and decreasing trends.” They also note “no spatial structure was found for stations exhibiting trends.” Thus, they conclude, “there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States.”

Much the same was reported for Canada by Cunderlik and Ouarda (2009), who evaluated trends in the timing and magnitude of seasonal maximum flood events based on data obtained from 162 stations of the Reference Hydrometric Basin Network established by Environment Canada over the 30-year period 1974–2003. The Canadian researchers report finding “only 10% of the analyzed stations show

significant trends in the timing of snowmelt floods during the last three decades (1974–2003),” and they say these results imply “the occurrence of snowmelt floods is shifting towards the earlier times of the year,” as would be expected in a warming world. They note most of the identified trends “are only weakly or medium significant results” and “no significant trends were found in the timing of rainfall-dominated flood events.”

With respect to flood magnitudes, the two scientists state the trends they observed “are much more pronounced than the trends in the timing of the floods,” but most of these trends “had negative signs, suggesting that the magnitude of the annual maximum floods has been decreasing over the last three decades.” In addition, they found “the level of significance was also higher in these trends compared to the level of significance of the trends in the timing of annual maximum floods.”

A number of studies have examined floods over much longer intervals of time. Wolfe *et al.* (2005), for example, conducted a multiproxy hydroecological analysis of Spruce Island Lake (58°51'N, 111°29'W), a shallow, isolated, upland lake in a bedrock basin located in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta, Canada, in an attempt to assess the impacts of both natural variability and anthropogenic change on the hydroecology of the region over the past 300 years. Specifically, their research was designed to answer three questions: (1) Have hydroecological conditions in Spruce Island Lake since 1968 (the year in which river flow became regulated from hydroelectric power generation at the headwaters of the Peace River) varied beyond the range of natural variation of the past 300 years? (2) Is there evidence that flow regulation of the Peace River has caused significant changes in hydroecological conditions in Spruce Island Lake? (3) How is hydroecological variability at Spruce Island Lake related to natural climatic variability and Peace River flood history?

Wolfe *et al.*'s research revealed hydroecological conditions varied substantially over the past 300 years, especially in terms of multidecadal dry and wet periods. For question #1, the authors found hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with both “markedly wetter and drier conditions compared to recent decades” having occurred prior to the time of Peace River flow regulation. With respect to question #2, they note the current drying trend is not the

product of Peace River flow regulation, but rather the product of an extended drying period initiated in the early to mid-1900s. Lastly, with respect to question #3, Wolfe *et al.* found the multi-proxy hydroecological variables they analyzed were well correlated with other reconstructed records of natural climate variability, indicating a likely climatic influence on Spruce Island Lake hydroecological conditions over the period of record.

Thus there is nothing unusual about recent trends in the hydroecology of the Spruce Island Lake region. Wet and dry conditions of today fall well within the range of natural variability and show no fingerprint of anthropogenic global warming. What is more, they even bear no fingerprint of anthropogenic flow control on the Peace River since 1968, demonstrating, in the words of the authors, that “profound changes in hydro-ecological conditions are clearly a natural feature of this ecosystem, independent of human influence or intervention.”

Shapley *et al.* (2005) developed a 1,000-year hydroclimate reconstruction from local bur oak (*Quercus macrocarpa*) tree-ring records and lake sediment cores from the Waubay Lake complex located in eastern South Dakota. During the 1990s, broad areas of the U.S. Northern Great Plains experienced notable lake highstands. Waubay Lake, for example, rose by 5.7 meters and more than doubled in area from 1993 to 1999, severely flooding roads, farms, and towns and prompting the Federal Emergency Management Agency to declare the region a disaster area on 1 June 1998. Shapley *et al.* set out to determine the historical context of that 1990s lake-level rise.

The researchers found “prior to AD 1800, both lake highstands and droughts tended towards greater persistence than during the past two centuries,” such that “neither generally low lake levels occurring since European settlement (but before the recent flooding) nor the post-1930s pattern of steadily increasing water availability and favorableness for tree growth are typical of the long-term record.” In this particular part of the world, longer-lasting floods and droughts of equal or greater magnitude than those of modern times occurred repeatedly prior to 1800.

Fye *et al.* (2003) developed multicentury reconstructions of summer (June–August) Palmer Drought Severity Index over the continental United States from annual proxies of moisture status provided by 426 climatically sensitive tree-ring chronologies. They found the greatest twentieth century wetness anomaly across the United States was

the 13-year pluvial that occurred in the early part of the century, when it was considerably colder than it is now. Fye *et al.*'s analysis also revealed the existence of a 16-year pluvial from 1825 to 1840 and a prolonged 21-year wet period from 1602 to 1622, both of which occurred during the Little Ice Age.

St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin to reconstruct annual precipitation in southern Manitoba since A.D. 1409." They found, "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement."

Ni *et al.* (2002) used tree-ring chronologies to develop a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico, USA. They found several wet periods comparable to the wet conditions seen in the early 1900s and post-1976 occurred in 1108–1120, 1195–1204, 1330–1345 (which they denote "the most persistent and extreme wet interval"), the 1610s, and the early 1800s. All of these wet periods are embedded in the long cold expanse of the Little Ice Age.

Ely (1997) wrote "paleoflood records from nineteen rivers in Arizona and southern Utah, including over 150 radiocarbon dates and evidence of over 250 flood deposits, were combined to identify regional variations in the frequency of extreme floods," and this information "was then compared with paleoclimatic data to determine how the temporal and spatial patterns in the occurrence of floods reflect the prevailing climate." The results of this comparison indicated "long-term variations in the frequency of extreme floods over the Holocene are related to changes in the climate and prevailing large-scale atmospheric circulation patterns that affect the conditions conducive to extreme flood-generating storms in each region." These changes, in Ely's view, "are very plausibly related to global-scale changes in the climate system."

With respect to the Colorado River watershed, for example, which integrates a large portion of the interior western United States, she writes "the largest floods tend to be from spring snowmelt after winters of heavy snow accumulation in the mountains of Utah, western Colorado, and northern New Mexico," such as occurred with the "cluster of floods from 5 to 3.6 ka," which occurred in conjunction with "glacial

advances in mountain ranges throughout the western United States" during the "cool, wet period immediately following the warm mid-Holocene."

The frequency of extreme floods also increased during the early and middle portions of the first millennium AD, many of which coincided "with glacial advances and cool, moist conditions both in the western U.S. and globally." Then came a "sharp drop in the frequency of large floods in the southwest from AD 1100–1300," which corresponded, in her words, "to the widespread Medieval Warm Period, which was first noted in European historical records." With the advent of the Little Ice Age, there was another "substantial jump in the number of floods in the southwestern U.S.," which was "associated with a switch to glacial advances, high lake levels, and cooler, wetter conditions."

Distilling her findings to a single succinct statement, and speaking specifically of the southwestern United States, Ely writes, "global warm periods, such as the Medieval Warm Period, are times of dramatic decreases in the number of high-magnitude floods in this region."

Schimmelmann *et al.* (2003) analyzed gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, USA, which they accurately dated by varve-counting. They found six prominent flood events at approximately AD 212, 440, 603, 1029, 1418, and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200, and 1800. They further note "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells"; "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)"; and "the flood of ~AD 1418 occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al.*, 1997; Meeker and Mayewski, 2002)." They hypothesize "solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years," and "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century." If such flooding occurs in the near future, there will be

no need to suppose it came as a consequence of what the IPCC calls the unprecedented warming of the past century.

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of streamflow variability for this part of North America over the past 4,000 years. This work revealed the highest rates of stream discharge during this period occurred during the Little Ice Age, approximately 300–350 years ago, at which time grain sizes were about 2.5 standard deviations above the 4,000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, during the Medieval Warm Period, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean.

Carson *et al.* (2007) developed a Holocene history of flood magnitudes from reconstructed cross-sectional areas of abandoned channels and relationships relating channel cross-sections to flood magnitudes derived from modern stream gauge and channel records for the northern Uinta Mountains of northeastern Utah. Carson *et al.* report over the past 5,000 years the record of bankfull discharge “corresponds well with independent paleoclimate data for the Uinta Mountains,” and “during this period, the magnitude of the modal flood is smaller than modern during warm dry intervals and greater than modern during cool wet intervals,” noting most particularly “the decrease in flood magnitudes following 1000 cal yr B.P. corresponds to numerous local and regional records of warming during the Medieval Climatic Anomaly.” The three largest negative departures from modern bankfull flood magnitudes (indicating greater than modern warmth) range approximately 15–22%, as best as can be determined from visual inspection of their plotted data, and they occur between about 750 and 600 cal yr B.P., as determined from radiocarbon dating of basal channel-fill sediments.

Carson *et al.*’s findings demonstrate the degree of natural variability in northeastern Utah flood magnitudes throughout the Holocene has been much larger (in both positive and negative directions) than what has been observed in modern times. Moreover, their work demonstrates the portion of the Medieval Warm Period between about AD 1250 and 1400 was likely significantly warmer than it is at present. Something other than high concentrations of atmospheric CO₂ was responsible for the region’s warmth at that time, and thus one need not invoke today’s much higher CO₂ concentrations as the reason

for our actually lower current temperatures.

Brown *et al.* (1999) analyzed properties of cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow over the past 5,300 years. They found evidence of seven large megafloods, which they describe as “almost certainly larger than historical floods in the Mississippi watershed.” They say these fluvial events were likely “episodes of multidecadal duration,” five of which occurred during cold periods similar to the Little Ice Age.

Noren *et al.* (2002) employed several techniques to identify and date terrigenous in-wash layers found in sediment cores extracted from 13 small lakes distributed across a 20,000-km² region in Vermont and eastern New York that depict the frequency of storm-related floods. Their results indicate “the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr.” Specifically, they found four major peaks in the data during this period, with the most recent upswing in storm-related floods beginning “at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age.” In addition, they note several “independent records of storminess and flooding from around the North Atlantic show maxima that correspond to those that characterize our lake records [Brown *et al.*, 1999; Knox, 1999; Lamb, 1979; Liu and Fearn, 2000; Zong and Tooley, 1999].”

Hirsch and Ryberg (2012) point out “one of the anticipated hydrological impacts of increases in greenhouse gas concentrations in the atmosphere is an increase in the magnitude of floods,” citing Trenberth (1999), the IPCC (2007), and Gutowski *et al.* (2008). Working with the global mean carbon dioxide concentration (GMCO₂) and a streamflow dataset consisting of long-term (85- to 127-year) annual flood series from 200 stream gauges deployed by the U.S. Geological Survey in basins with little or no reservoir storage or urban development (less than 150 persons per square kilometer in AD 2000) throughout the conterminous United States, which they divided into four large regions, Hirsch and Ryberg employed a stationary bootstrapping technique to determine whether the patterns of the statistical associations between the two parameters were significantly different from what would be expected under the null hypothesis that flood magnitudes are independent of GMCO₂.

The two researchers report “in none of the four

Observations: Extreme Weather

regions defined in this study is there strong statistical evidence for flood magnitudes increasing with increasing GMCO₂.” One region, the southwest, showed a statistically significant negative relationship between GMCO₂ and flood magnitudes. Hirsch and Ryberg conclude “it may be that the greenhouse forcing is not yet sufficiently large to produce changes in flood behavior that rise above the ‘noise’ in the flood-producing processes.” It could also mean the “anticipated hydrological impacts” envisioned by the IPCC and others are simply incorrect.

Taken together, the research described in this subsection suggest, if anything, that North American flooding tends to become less frequent and less severe when the planet warms, although there have been exceptions to this general rule. Although there could be exceptions to this rule in the future, it is more likely than not that any further warming of the globe would tend to further reduce both the frequency and severity of flooding in North America—just the opposite of what climate models suggest would occur.

References

- Brown, P., Kennett, J.P., and Ingram, B.L. 1999. Marine evidence for episodic Holocene megafloods in North America and the northern Gulf of Mexico. *Paleoceanography* **14**: 498–510.
- Campbell, C. 2002. Late Holocene lake sedimentology and climate change in southern Alberta, Canada. *Quaternary Research* **49**: 96–101.
- Carson, E.C., Knox, J.C., and Mickelson, D.M. 2007. Response of bankfull flood magnitudes to Holocene climate change, Uinta Mountains, northeastern Utah. *Geological Society of America Bulletin* **119**: 1066–1078.
- Cunderlik, J.M. and Ouarda, T.B.M.J. 2009. Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology* **375**: 471–480.
- Ely, L.L. 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. *Geomorphology* **19**: 175–201.
- Fye, F.K., Stahle, D.W., and Cook, E.R. 2003. Paleoclimatic analogs to twentieth-century moisture regimes across the United States. *Bulletin of the American Meteorological Society* **84**: 901–909.
- Garbrecht, J.D. and Rossel, F.E. 2002. Decade-scale precipitation increase in Great Plains at end of 20th century. *Journal of Hydrologic Engineering* **7**: 64–75.
- Gutowski Jr., W.J., Hegerl, G.C., Holland, G.J., Knutson, T.R., Mearns, L.O., Stouffer, R.J., Webster, P.J., Wehner, M.F., Zwiers, F.W., Brooks, H.E., Emanuel, K.A., Kormar, P.D., Kossin, J.P., Kunkel, K.E., McDonald, R., Meehl, G.A., and Trapp, R.J. 2008. Causes of observed changes in extremes and projections of future changes. In: Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M., and Murray, W.L. (Eds.) *Weather and Climate Extremes in a Changing Climate-Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. U.S. Climate Change Science, Washington, DC, USA.
- Haque, C.E. 2000. Risk assessment, emergency preparedness and response to hazards: The case of the 1997 Red River Valley flood, Canada. *Natural Hazards* **21**: 225–245.
- Hirsch, R.M. and Ryberg, K.R. 2012. Has the magnitude of floods across the USA changed with global CO₂ levels? *Hydrological Sciences Journal* **57**: 10.1080/02626667.2011.621895.
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis*. Solomon, S., Qin, D., Manniing, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- Kennett, D.J. and Kennett, J.P. 2000. Competitive and cooperative responses to climatic instability in coastal southern California. *American Antiquity* **65**: 379–395.
- Knox, J.C. 1999. Sensitivity of modern and Holocene floods to climate change. *Quaternary Science Reviews* **19**: 439–457.
- Knox, J.C. 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *Catena* **42**: 193–224.
- Kreutz, K.J., Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S.I., and Pittalwala, I.I. 1997. Bipolar changes in atmospheric circulation during the Little Ice Age. *Science* **277**: 1294–1296.
- Lamb, H.H. 1979. Variation and changes in the wind and ocean circulation: the Little Ice Age in the northeast Atlantic. *Quaternary Research* **11**: 1–20.
- Lins, H.F. and Slack, J.R. 1999. Streamflow trends in the United States. *Geophysical Research Letters* **26**: 227–230.
- Liu, K.-b. and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* **54**: 238–245.
- Meeker, L.D. and Mayewski, P.A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* **12**: 257–266.

- Molnar, P. and Ramirez, J.A. 2001. Recent trends in precipitation and streamflow in the Rio Puerco Basin. *Journal of Climate* **14**: 2317–2328.
- Ni, F., Cavazos, T., Hughes, M.K., Comrie, A.C., and Funkhouser, G. 2002. Cool-season precipitation in the southwestern USA since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* **22**: 1645–1662.
- Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., and Southon, J. 2002. Millennial-scale storminess variability in the northeastern United States during the Holocene epoch. *Nature* **419**: 821–824.
- Olsen, J.R., Stedinger, J.R., Matalas, N.C., and Stakhiv, E.Z. 1999. Climate variability and flood frequency estimation for the Upper Mississippi and Lower Missouri Rivers. *Journal of the American Water Resources Association* **35**: 1509–1523.
- Pinter, N., Jemberie, A.A., Remo, J.W.F., Heine, R.A., and Ickes, B.S. 2008. Flood trends and river engineering on the Mississippi River system. *Geophysical Research Letters* **35**: 10.1029/2008GL035987.
- Schimmelmann, A., Lange, C.B., and Meggers, B.J. 2003. Palaeoclimatic and archaeological evidence for a 200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. *The Holocene* **13**: 763–778.
- Shapley, M.D., Johnson, W.C., Engstrom, D.R., and Osterkamp, W.R. 2005. Late-Holocene flooding and drought in the Northern Great Plains, USA, reconstructed from tree rings, lake sediments and ancient shorelines. *The Holocene* **15**: 29–41.
- St. George, S. and Nielsen, E. 2002. Hydroclimatic change in southern Manitoba since A.D. 1409 inferred from tree rings. *Quaternary Research* **58**: 103–111.
- Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* **42**: 327–339.
- Villarini, G., Serinaldi, F., Smith, J.A., and Krajewski, W.F. 2009. On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resources Research* **45**: 10.1029/2008WR007645.
- Villarini, G. and Smith, J.A. 2010. Flood peak distributions for the eastern United States. *Water Resources Research* **46**: 10.1029/2009WR008395.
- Villarini, G., Smith, J.A., Baeck, M.L., and Krajewski, W.F. 2011. Examining flood frequency distributions in the Midwest U.S. *Journal of the American Water Resources Association* **47**: 447–463.
- Wolfe, B.B., Karst-Riddoch, T.L., Vardy, S.R., Falcone, M.D., Hall, R.I., and Edwards, T.W.D. 2005. Impacts of climate and river flooding on the hydro-ecology of a floodplain basin, Peace-Athabasca Delta, Canada since A.D. 1700. *Quaternary Research* **64**: 147–162.
- Zong, Y. and Tooley, M.J. 1999. Evidence of mid-Holocene storm-surge deposits from Morecambe Bay, northwest England: A biostratigraphical approach. *Quaternary International* **55**: 43–50.

7.5.5 South America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to South America.

River flow records in southern South America, according to Mundo *et al.* (2012), “extend for only a few decades, hampering the detection of long-term, decadal to centennial-scale cycles and trends,” which are needed in order to ascertain the degree of validity of model-based claims for that part of the world.

To extend the streamflow history of Argentina’s Neuquen River—which Mundo *et al.* say is of “great importance for local and national socio-economic activities such as hydroelectric power generation, agriculture and tourism”—the authors employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of the river for each year of the 654-year period AD 1346–2000, using a nested principal component regression approach.

In terms of the frequency, intensity, and duration of droughts and pluvial events, the eight researchers determined “the 20th century contains some of the driest and wettest annual to decadal-scale events in the last 654 years.” They also report “longer and more severe events were recorded in previous centuries.”

Rein *et al.* (2004) derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima, Peru. The authors reported finding a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the late Medieval period. “Lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250,” they report, indicating a sustained

period absent of large floods. They state “all known terrestrial deposits of El Niño mega-floods (Magillan and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly.” In addition, they note “this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain,” citing 11 references.

References

- Magillan, F.J. and Goldstein, P.S. 2001. El Niño floods and culture change: A late Holocene flood history for the Rio Moquegua, southern Peru. *Geology* **29**: 431–434.
- Mundo, I.A., Masiokas, M.H., Villalba, R., Morales, M.S., Neukom, R., Le Quesne, C., Urrutia, R.B., and Lara, A. 2012. Multi-century tree-ring based reconstruction of the Neuquen River streamflow, northern Patagonia, Argentina. *Climate of the Past* **8**: 815–829.
- Philander, S.G.H. 1990. *El Niño, La Niña, and the Southern Oscillation*. Academic Press, San Diego, California, USA.
- Rein B., Lückge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.
- Wells, L.E. 1990. Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru. *Geology* **18**: 1134–1137.

7.6 Precipitation

The IPCC and others claim global warming will cause greater variability in precipitation, frequently manifested in climate models as more frequent and heavier rainfall events. The IPCC has stated “in the near term, it is likely that the frequency and intensity of heavy precipitation events will increase at the global scale and at high latitudes” (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). The IPCC expects changes in average precipitation as well; some regions will increase, others will decrease, but on the whole, global precipitation is expected to increase.

General trends in precipitation are examined in Chapter 6 of this volume, where observational data indicate there is nothing unusual or unprecedented about recent precipitation events and trends in most regions, suggesting rising atmospheric CO₂ is having no measurable effect on precipitation totals. This section focuses on the variability or extremeness of

precipitation, seeking to determine whether there is compelling evidence from historical observations that recent changes, if they are occurring, are the product of Earth’s rising atmospheric CO₂ concentration.

As revealed in the subsections below, numerous studies suggest there is, in fact, no CO₂ influence on the variability or extremeness of precipitation. Moisture extremes much greater than those observed in the modern era have occurred throughout the historic past. Recent trends and events are neither unusual nor manmade; they are simply a normal part of Earth’s natural climatic variability.

7.6.1 Africa

Nicholson and Yin (2001) describe climatic and hydrologic conditions in equatorial East Africa from the late 1700s to close to the present, based on histories of the levels of 10 major African lakes. They also use a water balance model to infer changes in rainfall associated with the different conditions, concentrating most heavily on Lake Victoria. This work reveals “two starkly contrasting climatic episodes.” The first, which began sometime prior to 1800 and was characteristic of Little Ice Age conditions, was one of “drought and desiccation throughout Africa.” This arid episode, which was most extreme during the 1820s and 1830s, was accompanied by extremely low lake levels. As the two researchers describe it, “Lake Naivash was reduced to a puddle ... Lake Chad was desiccated ... Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides ... Lake Rukwa [was] completely desiccated ... Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up.” Throughout this period, they report, “intense droughts were ubiquitous.” Some were “long and severe enough to force the migration of peoples and create warfare among various tribes.”

As the Little Ice Age’s grip on the world began to loosen in the mid to late 1800s, things began to improve for most of the continent. Nicholson and Yin report “semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests, ... the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region.” Across the length of the northern Sahel, maps and geographical reports described the presence of “forests.” As the nineteenth century came to an end and the twentieth century began, there was a slight lowering of lake levels, but nothing like what had occurred a century

earlier (i.e., the precipitation variability was much reduced). In the latter half of the twentieth century, the levels of some of the lakes rivaled the high-stands characteristic of the years of transition to the Current Warm Period.

Nicholson (2001) reports the most significant climatic change in the more recent past has been “a long-term reduction in rainfall in the semi-arid regions of West Africa,” which has been “on the order of 20 to 40% in parts of the Sahel.” There have been, she states, “three decades of protracted aridity,” and “nearly all of Africa has been affected ... particularly since the 1980s.” She goes on to note “the rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented” and “a similar dry episode prevailed during most of the first half of the 19th century.”

Nicholson says “the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of irreversible global change,” because a longer historical perspective indicates an even longer period of similar dry conditions occurred between 1800 and 1850. This dry period occurred when Earth was still in the clutches of the Little Ice Age, a period of cold that is without precedent in at least the past 6,500 years, even in Africa (Lee-Thorp *et al.*, 2001). There is therefore no reason to consider the most recent two- to three-decade Sahelian drought as unusual or the result of higher temperatures of that period.

Nguetsop *et al.* (2004) developed a high-resolution proxy record of West African precipitation based on analyses of diatoms recovered from a sediment core retrieved from Lake Ossa, West Cameroon, which they describe as “the first paleohydrological record for the last 5500 years in the equatorial near-coastal area, east of the Guinean Gulf.” They report this record provides evidence for alternating periods of increasing and decreasing precipitation “at a millennial time scale for the last 5500 years,” and they interpret this oscillatory behavior as being “a result of south/northward shifts of the Intertropical Convergence Zone,” specifically noting “a southward shift of the ITCZ, combined with strengthened northern trade winds, was marked by low and high precipitation at the northern subtropics and the subequatorial zone, respectively,” and “these events occurred in coincidence with cold spells in the northern Atlantic.”

Therrell *et al.* (2006) developed “the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical

hardwood known locally as Mukwa] from Zimbabwe.” This record revealed “a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995),” and “an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data.” They report the year 1860, which exhibited the lowest reconstructed rainfall value during this period, was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as “a season of ‘severe and universal drought’ with ‘food of every description’ being ‘exceedingly scarce’ and the losses of cattle being ‘very severe’ (Nash and Endfield, 2002).” At the other end of the moisture spectrum, they report “a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era.”

For a large part of central southern Africa, as well as other parts of the continent described above, it is clear twentieth century global warming has not resulted in an intensification of extreme dry and wet periods. If anything, just the opposite appears to have occurred.

References

- Lee-Thorp, J.A., Holmgren, K., Lauritzen, S.-E., Linge, H., Moberg, A., Partridge, T.C., Stevenson, C., and Tyson, P.D. 2001. Rapid climate shifts in the southern African interior throughout the mid to late Holocene. *Geophysical Research Letters* **28**: 4507–4510.
- Nash, D.J. and Endfield, G.H. 2002. A 19th-century climate chronology for the Kalahari region of central southern Africa derived from missionary correspondence. *International Journal of Climatology* **22**: 821–841.
- Nguetsop, V.F., Servant-Vildary, S., and Servant, M. 2004. Late Holocene climatic changes in west Africa, a high resolution diatom record from equatorial Cameroon. *Quaternary Science Reviews* **23**: 591–609.
- Nicholson, S.E. 2001. Climatic and environmental change in Africa during the last two centuries. *Climate Research* **17**: 123–144.
- Nicholson, S.E. and Yin, X. 2001. Rainfall conditions in equatorial East Africa during the Nineteenth Century as inferred from the record of Lake Victoria. *Climatic Change* **48**: 387–398.
- Therrell, M.D., Stahle, D.W., Ries, L.P., and Shugart, H.H. 2006. Tree-ring reconstructed rainfall variability in Zimbabwe. *Climate Dynamics* **26**: 677–685.

7.6.2 Asia

Pederson *et al.* (2001) developed tree-ring chronologies for northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Working with both standard deviations and 5-year intervals of extreme wet and dry periods, they found “variations over the recent period of instrumental data are not unusual relative to the prior record.” They note, however, their reconstructions “appear to show more frequent extended wet periods in more recent decades,” but this observation “does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models.” Spectral analysis of the data also revealed significant periodicities around 12 and 20–24 years, which they suggested may constitute “possible evidence for solar influences in these reconstructions for northeastern Mongolia.”

Davi *et al.* (2006) used absolutely dated tree-ring-width chronologies obtained from five sampling sites in west-central Mongolia to derive individual precipitation histories, the longest of which stretches from 1340 to 2002, additionally developing a reconstruction of streamflow that extends from 1637 to 1997. They discovered there was “much wider variation in the long-term tree-ring record than in the limited record of measured precipitation,” which for the region they studied covers the period from 1937 to 2003. In addition, they say their streamflow history indicates “the wettest 5-year period was 1764–68 and the driest period was 1854–58,” and “the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83.”

Liu *et al.* (2012) state “climate change is consistently associated with changes in a number of components of the hydrological cycle,” including “precipitation patterns and intensity, and extreme weather events.” Therefore, and in order to “provide advice for water resource management under climate change,” they conducted a study of the subject in the Guangdong Province of Southern China, which occupies a land area of approximately 178,000 km² and has a population of just over 96 million people (as of 2009). The authors analyzed “trends of annual, seasonal and monthly precipitation in southern China (Guangdong Province) for the period 1956–2000 ... based on the data from 186 high-quality gauging stations,” and they employed “statistical tests, including the Mann-Kendall rank test and wavelet analysis,” to determine whether the precipitation series exhibited any regular trends or periodicities.

The four researchers report “annual precipitation

has a slightly decreasing trend in central Guangdong and slight increasing trends in the eastern and western areas of the province,” but “all the annual trends are not statistically significant at the 95% confidence level.” They discovered “average precipitation increases in the dry season in central Guangdong, but decreases in the wet season,” such that “precipitation becomes more evenly distributed within the year.” They state “the results of wavelet analysis show prominent precipitation with periods ranging from 10 to 12 years in every sub-region in Guangdong Province.” Comparing precipitation with the 11-year sunspot cycle, they find “the annual precipitation in every sub-region in Guangdong province correlates with Sunspot Number with a 3-year lag.” Thus, rather than becoming more extreme in the face of 1956–2000 global warming, precipitation in China’s Guangdong Province appears to have become both less extreme and less variable. The precipitation patterns that emerge upon proper analysis suggest the primary player in their determination is the Sun.

Ji *et al.* (2005) used reflectance spectroscopy on a sediment core taken from a lake in the northeastern part of the Qinghai-Tibetan Plateau to obtain a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. They found monsoonal moisture since the late glacial period had been subject to “continual and cyclic variations,” among which was a “very abrupt onset and termination” of a 2,000-year dry spell that started about 4,200 years ago (yr BP) and ended around 2300 yr BP. Other variations included the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age (LIA), which lasted from 2100 yr BP to 1800 yr BP and 780 yr BP to 400 yr BP, respectively, while sandwiched between them was the warmer and wetter Medieval Warm Period, and preceding the DACP was the Roman Warm Period.

Time series analyses of the sediment record also revealed several statistically significant periodicities (123, 163, 200, and 293 years, all above the 95% level), with the 200-year cycle matching the de Vries or Suess solar cycle, implying changes in solar activity are important triggers for some of the recurring precipitation changes in that part of Asia. Ji *et al.*’s study shows large and abrupt fluctuations in the Asian monsoon have occurred numerous times and with great regularity throughout the Holocene, and the Sun played an important role in orchestrating those fluctuations.

Shao *et al.* (2005) used seven Qilian juniper ring-

width chronologies from the northeastern part of the Qaidam Basin in the Tibetan Plateau to reconstruct a thousand-year history of annual precipitation. They discovered annual precipitation had fluctuated at various intervals and to various degrees throughout the past millennium. Wetter periods occurred between 1520 and 1633, as well as between 1933 and 2001, although precipitation has declined somewhat since the 1990s. Drier periods occurred between 1429 and 1519 and between 1634 and 1741. With respect to variability, the scientists report the magnitude of variation in annual precipitation was about 15 mm before 1430, increased to 30 mm between 1430 and 1850, and declined thereafter to the present. These findings together suggest the planet's current warmth is not unprecedented relative to that of the early part of the past millennium, or unprecedented warming need not lead to unprecedented precipitation or unprecedented precipitation variability, or both. This study does not provide support for the contention that global warming leads to greater and more frequent precipitation extremes.

Zhang *et al.* (2007) developed flood and drought histories of the past thousand years in China's Yangtze Delta "from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," upon which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." In comparing their findings with two one-thousand-year temperature histories from the region, the authors report "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region." In addition, during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred" in the flood/drought series.

In contrast, Zhang *et al.* report during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region." These findings once again illustrate warmer climates tend to be less variable than colder ones.

Touchan *et al.* (2005) developed summer (May–

August) precipitation reconstructions for several parts of the eastern Mediterranean region (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back in time from 115 to 600 years. Over the latter period of time, they found May–August precipitation varied on multiannual and decadal timescales, but on the whole there were no long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods: 1601–1605 and 1751–1755. In addition, both extremely strong and weak precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930. This study thus also demonstrates there was nothing unusual or unprecedented about late-twentieth century precipitation events in the eastern Mediterranean part of Asia that would suggest a CO₂ influence. If anything, as this region transited from the record cold of the Little Ice Age to the peak warmth of the Current Warm Period, May–August precipitation became less variable in the face of rising temperatures.

Kripalani and Kulkarni (2001) studied seasonal summer monsoon (June–September) rainfall data from 120 east Asia stations for the period 1881–1998. A series of statistical tests they applied to these data revealed the presence of short-term variability in rainfall amounts on decadal and longer time scales, the longer "epochs" of which were found to last for about three decades over China and India and for approximately five decades over Japan. No long-term trends were detected. With respect to the decadal variability found in the record, the two researchers say it "appears to be just a part of natural climate variations."

Kishtawal *et al.* (2010) studied the Indian subcontinent (8.2°N to 35.35°N, 68.5°E to 97°E) to assess the impacts of urbanization on the region's rainfall characteristics during the Indian summer monsoon by analyzing *in situ* and satellite-based precipitation and population datasets. The five researchers found "a significantly increasing trend in the frequency of heavy rainfall climatology over urban regions of India during the monsoon season," adding "urban regions experience less occurrences of light rainfall and significantly higher occurrences of intense precipitation compared to non-urban regions."

What is the significance of these findings? In their book *Dire Predictions: Understanding Global Warming*, Mann and Kump (2008) note most climate model simulations of global warming indicate "increases are to be expected in the frequency of very intense rainfall events." Throughout most of the

world, however, and as seen in the studies reviewed in this section, that expectation has not been fulfilled. Where increasing frequency of intense rainfall events has been observed in some studies, the findings of Kishtawal *et al.* and the papers they cite suggest urbanization may have been the cause. Moreover, the work of Hossain *et al.* (2009) suggests the proliferation of large dams also may be causing such events to occur. The work reviewed here suggests the only effect CO₂-induced global warming may be having on precipitation variability in Asia is to make it less rather than more variable.

References

- Davi, N.K., Jacoby, G.C., Curtis, A.E., and Baatarbileg, N. 2006. Extension of drought records for Central Asia using tree rings: West-Central Mongolia. *Journal of Climate* **19**: 288–299.
- Hossain, F., Jeyachandran, I., and Pielke Sr., R. 2009. Have large dams altered extreme precipitation patterns? *EOS, Transactions, American Geophysical Union* **90**: 453–454.
- Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L., and Liu, X. 2005. Asian monsoon oscillations in the northeastern Qinghai-Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters* **233**: 61–70.
- Kishtawal, C.M., Niyogi, D., Tewari, M., Pielke Sr., R.A., and Shepherd, J.M. 2010. Urbanization signature in the observed heavy rainfall climatology over India. *International Journal of Climatology* **30**: 1908–1916.
- Kripalani, R.H. and Kulkarni, A. 2001. Monsoon rainfall variations and teleconnections over south and east Asia. *International Journal of Climatology* **21**: 603–616.
- Liu, D., Guo, S., Chen, X., and Shao, Q. 2012. Analysis of trends of annual and seasonal precipitation from 1956 to 2000 in Guangdong Province, China. *Hydrological Sciences Journal* **57**: 358–369.
- Mann, M.E. and Kump, L.R. 2008. *Dire Predictions: Understanding Global Warming*. DK Publishing, Inc., New York, New York, USA.
- Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. *Journal of Climate* **14**: 872–881.
- Shao, X., Huang, L., Liu, H., Liang, E., Fang, X., and Wang, L. 2005. Reconstruction of precipitation variation from tree rings in recent 1000 years in Delingha, Qinghai. *Science in China Series D: Earth Sciences* **48**: 939–949.
- Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M.K., Erkan, N., Akkemik, U., and Stephan, J. 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics* **25**: 75–98.
- Zhang, Q., Chen, J., and Becker, S. 2007. Flood/drought change of last millennium in the Yangtze Delta and its possible connections with Tibetan climatic changes. *Global and Planetary Change* **57**: 213–221.
- Zhao, C., Yu, Z., Zhao, Y., and Ito, E. 2009. Possible orographic and solar controls of Late Holocene centennial-scale moisture oscillations in the northeastern Tibetan Plateau. *Geophysical Research Letters* **36**: 10.1029/2009GL040951.

7.6.3 Europe

Alexandrov *et al.* (2004) analyzed various characteristics of climate in Bulgaria during the twentieth century by applying Meteo-France homogenization procedures to many raw datasets of the country, which procedures included, in their words, “control of monthly data of precipitation and average air temperature from selected weather stations in Bulgaria; detection of breaks and outliers within the collected and controlled time series; correction of the climate long-term series according to the defined breaks and outliers in order to obtain homogenized climate series.” They found “no significant warming trend during the last century in Bulgaria in spite of the slight increase of average air temperature during the last two decades.” They also note “a decreasing trend in annual and especially summer precipitation from the end of the 1970s was found,” and “variations of annual precipitation in Bulgaria showed an overall decrease.” Thus, as Bulgaria experienced a slight increase in average air temperature over the past two decades, the variability of annual precipitation decreased.

Ntegeka and Willems (2008) write “long-term temporal analysis of trends and cycles is crucial in understanding the natural variability within the climate system.” They performed “an empirical statistical analysis of trends in rainfall extremes ... based on the long-term high-frequency homogeneous rainfall series at the climatological station of the Royal Meteorological Institute of Belgium at Uccle.” This series was recorded by “the same measuring instrument at the same location since 1898 and processed with identical quality since that time,” and it was done at a measuring frequency of ten minutes,

yielding more than 107 years of continuous data.

The Belgian researchers report “significant deviations in rainfall quantiles were found, which persisted for periods of 10 to 15 years,” such that “in the winter and summer seasons, high extremes were clustered in the 1910s–1920s, the 1960s and recently in the 1990s.” “This temporal clustering,” the authors conclude, “highlights the difficulty of attributing ‘change’ in climate series to anthropogenically induced global warming,” and they state “no strong conclusions can be drawn on the evidence of the climate change effect in the historical rainfall series.”

Bohm (2012) notes “South Central Europe is among the spatially densest regions in terms of early instrumental climate data,” citing Auer *et al.* (2007). He states this allows for successfully testing for homogeneity and developing “a larger number of very long instrumental climate time series at monthly resolution than elsewhere,” which he thus proceeds to do. He notes the resulting long time series subset of the greater alpine region provides great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the “anthropogenic climate” of the past three decades. He reports “the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year ‘normal periods’ from 1771–1800 to 1981–2010.”

Bohm concludes “the overwhelming majority of seasonal and annual sub-regional variability trends is not significant.” In the case of precipitation, he writes, “there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period,” and in the case of temperature he reports “most of the variability trends are insignificantly decreasing.” In a “special analysis” of the recent 1981–2010 period that may be considered the first “normal period” under dominant greenhouse-gas-forcing, he finds all extremes “remaining well within the range of the preceding ones under mainly natural forcing.” He notes “in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable.”

Bohm, an Austrian researcher at the Central Institute for Meteorology and Geodynamics in Vienna, concludes there is “clear evidence that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less

than more variable than the series of the preceding 30-year normal period.”

References

Alexandrov, V., Schneider, M., Koleva, E., and Moisselin, J.-M. 2004. Climate variability and change in Bulgaria during the 20th century. *Theoretical and Applied Climatology* 79: 133–149.

Auer, I., Boehm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schoener, W., Ungersboeck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M., Mueller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cegnar, T., Dolinar, M., Gajic-Capka, M., Zaninovic, K., and Majstorovic, Z. 2007. HISTALP—Historical Instrumental climatological Surface Time series of the greater ALPine Region. *International Journal of Climatology* 27: 17–46.

Bohm, R. 2012. Changes of regional climate variability in central Europe during the past 250 years. *The European Physical Journal Plus* 127: 10.1140/epjp/i2012-12054-6.

Ntegeka, V. and Willems, P. 2008. Trends and multidecadal oscillations in rainfall extremes, based on a more than 100-year time series of 10 min rainfall intensities at Uccle, Belgium. *Water Resources Research* 44: 10.1029/2007WR006471.

7.6.4 North America

Cronin *et al.* (2000) studied salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United States, in an effort to determine precipitation variability in the surrounding watershed over the prior millennium. They discovered a high degree of decadal and multidecadal variability in moisture conditions over the 1,000-year period, with regional precipitation totals fluctuating by between 25% and 30%, often in extremely rapid shifts occurring over about a decade. They also determined precipitation was generally greater over the past two centuries than over the eight previous centuries, with the exception of a portion of the Medieval Warm Period (AD 1250–1350) when the climate was extremely wet. In addition, they found the region surrounding Chesapeake Bay had experienced several “megadroughts” lasting 60–70 years, some of which the researchers say “were more severe than twentieth century droughts.”

Across the continent, Haston and Michaelsen (1997) developed a 400-year history of precipitation

for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies. Their work revealed “region-wide precipitation during the last 100 years has been unusually high and less variable compared to other periods in the past.”

Watanabe *et al.* (2001) analyzed delta $^{18}\text{O}/^{16}\text{O}$ and Mg/Ca ratios in cores obtained from a coral in the Caribbean Sea to examine seasonal variability in sea surface temperature and salinity during the Little Ice Age. They found sea surface temperatures during this period were about 2°C colder than they are currently, and sea surface salinity exhibited greater variability than it does now, indicating during the Little Ice Age “wet and dry seasons were more pronounced.”

Zhang *et al.* (2001) analyzed the spatial and temporal characteristics of extreme precipitation events for the period 1900–1998 in Canada, using what they describe as “the most homogeneous long-term dataset currently available for Canadian daily precipitation.” The evidence indicated decadal-scale variability was a dominant feature of both the frequency and intensity of extreme precipitation events, but it provided “no evidence of any significant long-term changes” in these indices during the twentieth century. The authors’ analysis of precipitation totals (extreme and non-extreme) revealed a slightly increasing trend across Canada during the period of study, but it was found to be due to increases in the number of non-heavy precipitation events. Consequently, the researchers conclude “increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada.”

Tian *et al.* (2006) derived a high-resolution $\delta^{18}\text{O}$ record of endogenic calcite obtained from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. They found “the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods.” Most striking, they found “drought variability was anomalously low during the 20th century”—so low that “~90% of the variability values during the last 3100 years were greater than the 20th-century average.”

Gray *et al.* (2004) used cores extracted from 107 piñon pines at four different sites in the Uinta Basin Watershed of northeastern Utah to develop a proxy record of annual (June to June) precipitation spanning

the period AD 1226–2001. They report “single-year dry events before the instrumental period tended to be more severe than those after 1900,” and decadal-scale dry events were longer and more severe prior to 1900 as well. They note “dry events in the late 13th, 16th, and 18th centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900.” At the other end of the spectrum, they report the twentieth century contained two of the strongest wet intervals (1938–1952 and 1965–1987), representing the seventh and second most intense wet regimes, respectively, of the record.

Rasmussen *et al.* (2006) earlier had demonstrated “speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004).” In their present work, they continued this tack, concentrating on “two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1) in the Guadalupe Mountains.”

The three researchers report “both records, BC2 and HC1, suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record.” They also note the time interval of AD 900–1300 coincides with the well-known Medieval Warm Period and “shows dampened precipitation variability and overall drier conditions” “consistent with the idea of more frequent La Niña events and/or negative PDO phases causing elevated aridity in the region during this time.” They say the preceding and following colder centuries “show increased precipitation variability ... coinciding with increased El Niño flooding events.”

Clearly, moisture extremes in North America much greater than those observed in the modern era have occurred. Recent trends are neither unusual nor manmade; they are simply a normal part of Earth’s natural climatic variability. North America is like Africa, Asia, and Europe: Precipitation variability in the Current Warm Period is no greater than what was experienced in earlier times.

References

- Asmerom, Y. and Polyak, V.J. 2004. Comment on “A test of annual resolution in stalagmites using tree rings.” *Quaternary Research* **61**: 119–121.
- Cronin, T., Willard, D., Karlsen, A., Ishman, S., Verardo,

S., McGeehin, J., Kerhin, R., Holmes, C., Colman, S., and Zimmerman, A. 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments. *Geology* **28**: 3–6.

Gray, S.T., Jackson, S.T., and Betancourt, J.L. 2004. Tree-ring based reconstructions of interannual to decadal scale precipitation variability for northeastern Utah since 1226 A.D. *Journal of the American Water Resources Association* **40**: 947–960.

Haston, L. and Michaelsen, J. 1997. Spatial and temporal variability of southern California precipitation over the last 400 yr and relationships to atmospheric circulation patterns. *Journal of Climate* **10**: 1836–1852.

Rasmussen, J.B.T., Polyak, V.J. and Asmerom, Y. 2006. Evidence for Pacific-modulated precipitation variability during the late Holocene from the southwestern USA. *Geophysical Research Letters* **33**: 10.1029/2006GL025714.

Tian, J., Nelson, D.M., and Hu, F.S. 2006. Possible linkages of late-Holocene drought in the North American mid-continent to Pacific Decadal Oscillation and solar activity. *Geophysical Research Letters* **33**: 10.1029/2006GL028169.

Watanabe, T., Winter, A., and Oba, T. 2001. Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and $^{18}\text{O}/^{16}\text{O}$ ratios in corals. *Marine Geology* **173**: 21–35.

Zhang, X., Hogg, W.D., and Mekis, E. 2001. Spatial and temporal characteristics of heavy precipitation events over Canada. *Journal of Climate* **14**: 1923–1936.

7.7 Storms

Among the highly publicized changes in weather phenomena predicted to attend CO_2 -induced global warming are increases in the frequency and severity of various types of storms. Storms are a concern for the residents of any coastal city, as high winds, water surges, and high-energy waves can cause damage via flooding and erosion. It is therefore important to examine the historical records of storms for trends, to see if the so-named unprecedented rise in atmospheric CO_2 and temperature of the late twentieth and early twenty-first century has had any measurable effect on such storms.

Section 7.7 begins with an analysis of all types of storms by region (Sections 7.7.1.1 through 7.7.1.5), followed by a review of a specific type of storm (Dust Storms, Section 7.7.2) and three phenomena often associated with extreme storms (Hail, Section 7.7.3; Tornadoes, Section 7.7.4; and Wind, Section 7.7.5).

7.7.1 Regional Trends

For the globe as a whole, in its most recent *Assessment Report* the IPCC states “over the last century there is low confidence of a clear trend in storminess due to inconsistencies between studies or lack of long-term data in some parts of the world (particularly in the Southern Hemisphere),” adding “a reduction in the occurrence of Northern Hemisphere extratropical storms is likely, although, the most intense storms reaching Europe will likely increase in the strength” (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

The subsections of Section 7.7.1 examine what scientists have learned empirically about historic storm trends in an effort to understand how their past behavior has changed in relation to past temperatures. The results of that examination indicate storm frequency and intensity will not increase as a result of global warming.

7.7.1.1 Australia/New Zealand

De Lange and Gibb (2000) analyzed trends in sea-level data from several tide gauges located within Tauranga Harbor, New Zealand over the period 1960–1998. In an examination of seasonal, interannual, and decadal distributions of storm surge data, the two researchers identified a considerable decline in the annual number of storm surge events in the latter half of the nearly four-decade-long record. A similar trend also was noted in the magnitude of storm surges; and maximum water levels, including tides, also declined over the past two decades. Additionally, the authors found decadal variations in the data were linked to both the Interdecadal Pacific Oscillation (IPO) and the El Niño/Southern Oscillation (ENSO), such that La Niña events were associated with more storm surge days than El Niño events. Wavelet analyses of annual storm surge frequency data suggested before 1978 the frequency “was enhanced by the IPO, and subsequently it has been attenuated.”

Similar findings were reported a decade later by Page *et al.* (2010) who, working with sediment cores extracted from Lake Tutira on the eastern end of New Zealand’s North Island, developed a much longer 7,200-year history of the frequency and magnitude of storm activity, based on analyses of sediment grain size, diatom, pollen, and spore types and concentrations, carbon and nitrogen concentrations, and tephra and radiocarbon dating.

The ten New Zealanders plus one U.S. researcher report “the average frequency of all storm layers is

Observations: Extreme Weather

one in five years,” but “for storm layers ≥ 1.0 cm thick, the average frequency is every 53 years.” Over the course of their record, they state, “there are 25 periods with an increased frequency of large storms,” the onset and cessation of which “was usually abrupt, occurring on an inter-annual to decadal scale.” They also note the duration of these stormy periods “ranged mainly from several decades to a century,” but “a few were up to several centuries long,” and “intervals between stormy periods range from about thirty years to a century.” In addition, they find millennial-scale cooling periods tend to “coincide with periods of increased storminess in the Tutira record, while warmer events match less stormy periods.”

Page *et al.* comment there is growing concern, driven by climate models, that global warming may cause abrupt changes in various short-term meteorological phenomena, “when either rapid or gradual forces on components of the Earth system exceed a threshold or tipping point.” Their research shows the sudden occurrence of a string of years, or even decades, of unusually large storms is something that can happen at almost any time on its own, or at least without being driven by human activities such as the burning of fossil fuels.

Hayne and Chappell (2001) studied a series of storm ridges deposited over the past 5,000 years at Curacoa Island on the central Queensland shelf (18°40'S; 146°33'E), Australia, to create a history of major cyclonic events that have affected the area. They find “cyclone frequency was statistically constant over the last 5,000 years” and report “no indication that cyclones have changed in intensity.” They also note isotopic and trace element evidence from ancient corals indicate sea surface temperatures were about 1°C warmer about 5,000 years ago, and pollen spectra from lake sediments suggest rainfall at that time was about 20% higher than today. These results clearly indicate, at least for this location, that cyclone frequency and intensity do not respond to changes in temperature as climate models have predicted.

Alexander *et al.* (2011) point out “understanding the long-term variability of storm activity would give a much better perspective on how unusual recent climate variations have been.” They note “for southeast and eastern Australia some studies have been able to assess measures of storm activity over longer periods back to the 19th century (e.g., Alexander and Power, 2009; Rakich *et al.*, 2008), finding either a decline in the number of storms or reduction in the strength of zonal geostrophic wind

flow,” although these studies “were limited to the analysis of only one or two locations.”

The four researchers analyzed storminess across southeast Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century, finding “strong evidence for a significant reduction in intense wind events across SE Australia over the past century.” They note “in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease,” while “in terms of the regional average series,” they write, “all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter.”

Yu *et al.* (2012) write “strong storms including cyclones, hurricanes, typhoons and strong wind events have catastrophic impacts on coral reefs worldwide,” noting “Yu *et al.* (2004) suggested that the surface ages of well-preserved transported coral blocks could indicate the ages of past storm occurrences.” This inference, they state, “was further confirmed by the analysis of sedimentation rates and grain sizes of lagoon sediments from the same reef (Yu *et al.*, 2006; Yu *et al.*, 2009).”

Yu *et al.* (2012) sampled 102 individual coral colonies (coral blocks) and four reef blocks they found distributed across the northern reef flat of Heron Reef, precisely dating them via the thermal ionization mass spectrometry (TIMS) U-series method, to explore their utility as indicators of historical storm activities around the southern end of the Great Barrier Reef, an area frequently visited by cyclones and storms, as noted by Done (1993) and Puotinen (2004). Based on the age distribution and relative probability frequency analysis of the dated coral and reef blocks, the seven scientists determined “there were eight relatively stormy periods since AD 1900, i.e., 1904–1909, 1914–1916, 1935–1941, 1945–1960, 1965–1967, 1976–1977, 1983–1988 and 2001–2007.” Their yearly plot of the data clearly shows the very center of the twentieth century (1935–1965) to have been that century’s most sustained stormy period in the vicinity of Heron Reef.

Li *et al.* (2011), citing “unprecedented public concern” with respect to the impacts of climate change, set out to examine the variability and trends of storminess for the Perth, Australia metropolitan coast. They conducted an extensive set of analyses using observations of wave, wind, air pressure, and

water level over the period 1994–2008. The results of their analysis, in their view, would serve “to validate or invalidate the climate change hypothesis” that rising CO₂ concentrations are increasing the frequency and severity of storms.

As shown in Figure 7.7.1.1.1, all storm indices showed significant interannual variability over the period of record, but “no evidence of increasing (decreasing) trends in extreme storm power was identified to validate the wave climate change hypotheses for the Perth region.”

In spite of what the Intergovernmental Panel on Climate Change has characterized as unprecedented global warming over the past two decades, Perth (Australia) has not experienced an increase in storm frequency or intensity. The studies cited above give little reason to believe CO₂-induced global warming will lead to increases in the frequency and magnitude

of storms. Such claims are ungrounded in the peer-reviewed literature and have no basis in real-world observations.

References

Alexander, L.V. and Power, S. 2009. Severe storms inferred from 150 years of sub-daily pressure observations along Victoria’s ‘Shipwreck Coast.’ *Australian Meteorological and Oceanographic Journal* **58**: 129–133.

Alexander, L.V., Wang, X.L., Wan, H., and Trewin, B. 2011. Significant decline in storminess over southeast Australia since the late 19th century. *Australian Meteorological and Oceanographic Journal* **61**: 23–30.

De Lange, W.P. and Gibb, J.G. 2000. Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **34**: 419–434.

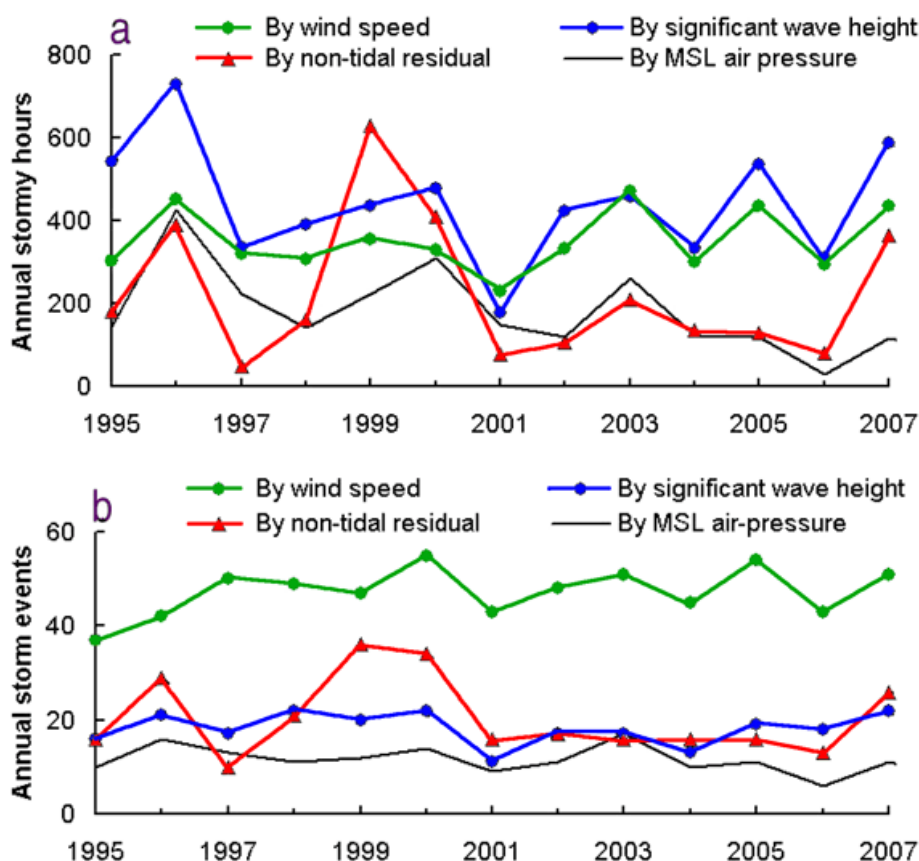


Figure 7.7.1.1.1. Annual storm trends for Perth, Australia defined by (a) stormy hours and (b) number of storm events, as determined by wind speed, significant wave height, non-tidal residual water level, and mean sea level pressure. Adapted from Li, F., Roncovich, L., Bicknell, C., Lowry, R., and Ilich, K. 2011. Interannual variability and trends of storminess, Perth, 1994–2008. *Journal of Coastal Research* **27**: 738–745.

Observations: Extreme Weather

Done, T. 1993. On tropical cyclones, corals and coral-reefs. *Coral Reefs* **12**: 126–126.

Hayne, M. and Chappell, J. 2001. Cyclone frequency during the last 5000 years at Curacoa Island, north Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **168**: 207–219.

Li, F., Roncevic, L., Bicknell, C., Lowry, R., and Ilich, K. 2011. Interannual variability and trends of storminess, Perth, 1994–2008. *Journal of Coastal Research* **27**: 738–745.

Page, M.J., Trustring, N.A., Orpin, A.R., Carter, L., Gomez, B., Cochran, U.A., Mildenhall, D.C., Rogers, K.M., Brackley, H.L., Palmer, A.S., and Northcote, L. 2010. Storm frequency and magnitude in response to Holocene climate variability, Lake Tutira, North-Eastern New Zealand. *Marine Geology* **270**: 30–44.

Puotinen, M.L. 2004. Tropical cyclones in the Great Barrier Reef, Australia, 1910–1999: a first step towards characterizing the disturbance regime. *Australian Geographical Studies* **42**: 378–392.

Rakich, C.S., Holbrook, N.J., and Timbal, B. 2008. A pressure gradient metric capturing planetary-scale influences on eastern Australian rainfall. *Geophysical Research Letters* **35**: 10.1029/2007GL032970.

Yu, K., Zhao, J., Roff, G., Lybolt, M., Feng, Y., Clark, T., and Li, S. 2012. High-precision U-series ages of transported coral blocks on Heron Reef (southern Great Barrier Reef) and storm activity during the past century. *Palaeogeography, Palaeoclimatology, Palaeoecology* **337–338**: 23–36.

Yu, K.F., Zhao, J.X., Collerson, K.D., Shi, Q., Chen, T.G.,

Wang, P.X., and Liu, T.S. 2004. Storm cycles in the last millennium recorded in Yongshu Reef, southern South China Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* **210**: 89–100.

Yu, K.F., Zhao, J.X., Shi, Q., and Meng, Q.S. 2009. Reconstruction of storm/tsunami records over the last 4000 years using transported coral blocks and lagoon sediments in the southern South China Sea. *Quaternary International* **195**: 128–137.

Yu, K.F., Zhao, J.X., Wang, P.X., Shi, Q., Meng, Q.S., Collerson, K.D., and Liu, T.S. 2006. High-precision TIMS U-series and AMS ¹⁴C dating of a coral reef lagoon sediment core from the southern South China Sea. *Quaternary Science Reviews* **25**: 2420–2430.

7.7.1.2 Europe

7.7.1.2.1 France

With respect to extreme weather events, Dezileau *et al.* (2011) write the major question of the day is, “are they linked to global warming or are they part of natural climate variability?” They say “it is essential to place such events in a broader context of time, and trace the history of climate changes over several centuries,” because “these extreme events are inherently rare and therefore difficult to observe in the period of a human life.”

Dezileau *et al.*, nine researchers from France, analyzed regional historical archives and sediment cores extracted from two Gulf of Aigues-Mortes lagoons in the northwestern part of the occidental Mediterranean Sea for bio- and geo-indicators of past storm activities there, assessing “the frequency and intensity of [extreme] events during the last 1500 years” as well as “links between past climatic conditions and storm activities.” The analysis showed evidence of four “catastrophic storms of category 3 intensity or more,” which occurred at approximately AD 455, 1742, 1848, and 1893. “Taking into account text description of the 1742 storm,” they conclude it was “of category more than 4 in intensity,” and all four of the storms “can be called superstorms.”

Dezileau *et al.* make a point of noting “the apparent increase in intense storms around 250 years ago lasts to about AD 1900,” whereupon “intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD).” They add, “interestingly, the two periods of most frequent superstorm strikes in the Aigues-Mortes Gulf (AD 455 and 1700–1900) coincide with two of the coldest periods in Europe during the late Holocene (Bond cycle 1 and the latter half of the Little Ice Age.)” The authors suggest “extreme storm events are associated with a large cooling of Europe,” and they calculate the risk of such storms occurring during that cold period “was higher than today by a factor of 10,” noting “if this regime came back today, the implications would be dramatic.”

Clarke *et al.* (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, finding dune formation was generally most common during cooler climatic intervals. In the most recent of these cold periods, the authors note there is voluminous historical evidence of many severe North Atlantic wind storms in which the southward spread of sea ice

and polar water likely created “an increased thermal gradient between 50°N and 65°N which intensified storm activity in the North Atlantic ... which may well have mobilized sand inland from the coast.” In addition, they note sand-drift episodes across Europe “show synchronicity with sand invasion in the Aquitaine region of southwest France, implying a regional response to increased storminess.” Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Working with historical accounts as well as “sedimentology, granulometry and faunistic data” obtained from two cores of the Pierre Blanche lagoon just south of Montpellier, France, Sabatier *et al.* (2008) found evidence of “washover events” that allowed them “to identify the strongest storms in the Mediterranean area” over the past four centuries. The eight researchers found “evidence of three main storms,” which they identified as occurring in 1742, 1839, and 1893, all of which were deemed to have been much stronger than any of the twentieth century. A storm that occurred in 1982, which they describe as having been “the most recent catastrophic event,” was not even “registered” in the lagoon sediment cores. Such a decline in the occurrence of “superstorms” in the Mediterranean area is a significant observation running counter to the model-based claim that global warming intensifies storms and brings more of them.

Sorrel *et al.* (2009) say studies indicate “estuarine systems are particularly sensitive to changing hydrological conditions,” and one of the major purposes of examining them has been to determine “the effects of past centennial- to millennial-scale natural climatic fluctuations” in order to “better predict the impact of present-day and forthcoming climatic changes (and/or anthropogenic activities) on estuary infill.” Of “crucial impact,” in their estimation, “is the impact of storminess within warmer and colder periods on sedimentary patterns through the climatic regulation of (i) coastal wave hydrodynamics and (ii) continental inputs from the Seine river catchment area [in the case of their specific study] during the late Holocene.”

Sorrel *et al.* linked high-resolution sediment and rock properties of materials found in cores collected from the Seine estuary in northwest France to climatic conditions of the past few thousand years. The five French researchers found “increased removal and transport of estuarine sediments occurred when winter storm activity greatly intensified over northwestern France,” and they report on “four prominent

centennial-scale periods of stronger storminess, occurring with a pacing of ~1500 years,” which they say are “likely to be related to the last four [of] Bond’s [1997, 2001] Holocene cold events,” the most recent of which was the Little Ice Age, when Sorrel *et al.* say tidal and open marine hydrodynamics exerted “primary control on the sedimentary evolution of the system during 1200–2003 AD.” In contrast, they found “the preservation of sedimentary successions in the outer Seine estuary was maximal during ca. 800–1200 AD,” which they identify as the Medieval Warm Period, when they say “sediment reworking by waves was considerably reduced.”

Sorrel *et al.* (2010) conducted a similar analysis for the macrotidal Bay of Vilaine (47°20'–47°35'N, 2°50'–2°30'W). Their results indicated “the late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives,” where the authors found “an increase in the contribution of riverine inputs occurred during the MWP [Medieval Warm Period]” at “times of strong fluvial influences in the estuary during ca. 880–1050 AD.” They also report “preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal,” in accordance with the findings of Proctor *et al.* (2000) and Meeker and Mayewski (2002). Furthermore, they state the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon *et al.* (2004) and Billeaud *et al.* (2005). They note, “all sedimentary records from the French and Spanish Atlantic coasts” suggest “the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development,” adding “milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths.”

Sorrell *et al.* (2010) also note the upper successions of the sediment cores “mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals,” while observing “this shift most probably documents the transition from the MWP to the Little Ice Age,” which led to the “increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and

Observations: Extreme Weather

Rendell, 2009)” associated with “the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard *et al.*, 2007; Clemmensen *et al.*, 2007, 2009; Matthews and Briffa, 2005), France (Meurisse *et al.*, 2005), Netherlands (Jelgersma *et al.*, 1995) and Scotland (Dawson *et al.*, 2004).” In what they call an even “wider perspective,” they note the Medieval Warm Period “is recognized as the warmest period of the last two millennia (Mayewski *et al.*, 2004; Moberg *et al.*, 2005).”

The French scientists conclude “the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD,” implying “climatic conditions were probably mild enough to prevent coastal erosion in northwestern France.”

Pirazzoli (2000) analyzed tide-gauge, wind, and atmospheric pressure data over the period 1951–1997 for the northern portion of the Atlantic coast of France. The author notes atmospheric depressions (storms) and strong surge winds “are becoming less frequent” in this region and “ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding” over the period of study. Such findings should be “reassuring,” Pirazzoli notes, especially for those concerned about coastal flooding.

The studies described above suggest there has been no significant increase in the frequency or intensity of stormy weather in France as Earth recovered from the global chill of the Little Ice Age. Storminess in most other parts of the planet also decreased over this period, as described in other subsections, suggesting there is no real-world, data-driven reason to believe storms would get any worse or become more frequent if Earth were to warm somewhat more in the future.

References

Aagaard, T., Orford, J., and Murray, A.S. 2007. Environmental controls on coastal dune formation: Skallingen Spit, Denmark. *Geomorphology* **83**: 29–47.

Billeaud, I., Chaumillon, E., and Weber, N. 2005. Evidence of a major environmental change recorded in a macrotidal bay (Marennes-Oleron Bay, France) by correlation between VHR seismic profiles and cores. *Geo-marine Letters* **25**: 1–10.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans,

M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climate. *Science* **278**: 1257–1266.

Chaumillon, E., Tessier, B., Weber, N., Tesson, M., and Bertin, X. 2004. Buried sandbodies within present-day estuaries (Atlantic coast of France) revealed by very high-resolution seismic surveys. *Marine Geology* **211**: 189–214.

Clarke, M.L. and Rendell, H.M. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International* **195**: 31–41.

Clarke, M.L., Rendell, H.M., Tastet, J-P., Clave, B., and Masse, L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. *The Holocene* **12**: 231–238.

Clemmensen, L.B., Bjornsen, M., Murray, A., and Pedersen, K. 2007. Formation of aeolian dunes on Anholt, Denmark since AD 1560: a record of deforestation and increased storminess. *Sedimentary Geology* **199**: 171–187.

Clemmensen, L.B., Murray, A., Heinemeier, J., and de Jong, R. 2009. The evolution of Holocene coastal dune fields, Jutland, Denmark: a record of climate change over the past 5000 years. *Geomorphology* **105**: 303–313.

Dawson, S., Smith, D.E., Jordan, J., and Dawson, A.G. 2004. Late Holocene coastal sand movements in the Outer Hebrides, NW Scotland. *Marine Geology* **210**: 281–306.

Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P., and Von Grafenstein, U. 2011. Intense storm activity during the Little Ice Age on the French Mediterranean coast. *Palaeogeography, Palaeoclimatology, Palaeoecology* **299**: 289–297.

Jelgersma, S., Stive, M.J.F., and van der Walk, L. 1995. Holocene storm surge signatures in the coastal dunes of the western Netherlands. *Marine Geology* **125**: 95–110.

Lamb, H.H. 1979. Climatic variations and changes in the wind and ocean circulation. *Quaternary Research* **11**: 1–20.

Matthews, J.A. and Briffa, K.R. 2005. The ‘Little Ice Age’: re-evaluation of an evolving concept. *Geografiska Annaler* **87A**: 17–36.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G.

Rack, F., Staubwasser, M., Schneider, R.R., and Steig, E.J. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.

Meeker, L.D. and Mayewski, P.A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* **12**: 257–266.

Meurisse, M., van Vliet-Lanoe, B., Talon, B., and Recourt, P. 2005. Complexes dunaires et tourbeux holocenes du littoral du Nord de la France. *Comptes Rendus Geosciences* **337**: 675–684.

Moberg, A., Sonechkin, K.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

Pirazzoli, P.A. 2000. Surges, atmospheric pressure and wind change and flooding probability on the Atlantic coast of France. *Oceanologica Acta* **23**: 643–661.

Proctor, C.J., Baker, A., Barnes, W.L., and Gilmour, M.A. 2000. A thousand year speleothem record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Sabatier, P., Dezileau, L., Condomines, M., Briquet, L., Colin, C., Bouchette, F., Le Duff, M., and Blanchemanche, P. 2008. Reconstruction of paleostorm events in a coastal lagoon (Herault, South of France). *Marine Geology* **251**: 224–232.

Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D., and Traini, C. 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): Depositional history and late Holocene climatic and environmental signals. *Continental Shelf Research* **30**: 1250–1266.

Sorrel, P., Tessier, B., Demory, F., Delsinne, N., and Mouaze, D. 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). *Quaternary Science Reviews* **28**: 499–516.

7.7.1.2.2 United Kingdom

Allan *et al.* (2009) point out an analysis of a 47-year storm database by Alexander *et al.* (2005) “showed an increase in the number of severe storms in the 1990s in the United Kingdom,” but “it was not possible to say with any certainty that this was either indicative of climatic change or unusual unless it was seen in a longer-term context.” Allan *et al.* extended the database of Alexander *et al.* back to 1920, almost doubling the length of the record, after which they reanalyzed the expanded dataset for the periods of boreal autumn (October, November, December) and

winter (January, February, March). They determined both databases exhibited peaks in storminess in the 1920s and 1990s, with boreal autumn storms being more numerous in the 1920s and winter storms being more numerous in the 1990s. The total storm numbers for each decade are plotted in Figure 7.7.1.2.2.1 As can be seen there, both the beginning and end decades of the record experienced nearly identical numbers of storms, demonstrating the increasingly greater number of extreme storms affecting the British Isles from the 1960s through the 1990s likely was not related to the global warming of that period.

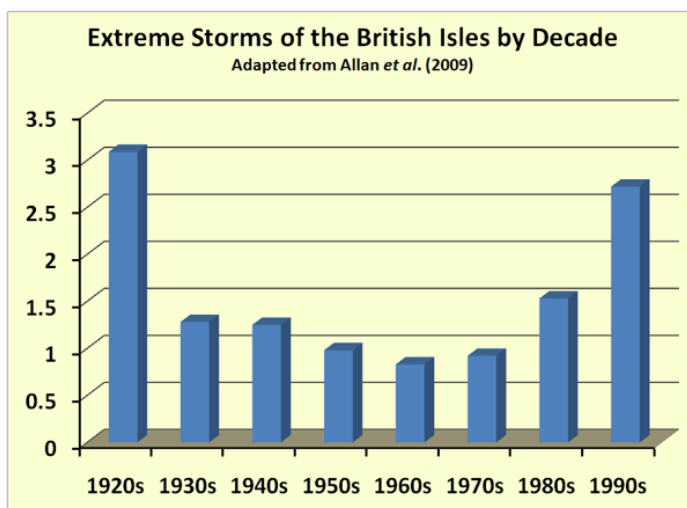


Figure 7.7.1.2.2.1. Number of extreme storms impacting the British Isles in each of eight decadal periods. Created from results reported by Allan, R., Tett, S., and Alexander, L. 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**: 357–371.

Dawson *et al.* (2002) searched daily meteorological records from northern and northwestern Scotland—Stornoway (Outer Hebrides), Lerwick (Shetland Islands), Wick (Caithness), and Fair Isle (west of the Shetland Islands)—for data pertaining to gale-force winds over the period 1876–1996, which they used to construct a history of storminess for that period. Although North Atlantic storminess and associated wave heights were found to have increased over the prior two decades, storminess in the North Atlantic region “was considerably more severe during parts of the nineteenth century than in recent decades.” In addition, whereas the modern increase in storminess appeared to be associated with a spate of substantial positive values of the North

Observations: Extreme Weather

Atlantic Oscillation (NAO) index, Dawson *et al.* state “this was not the case during the period of exceptional storminess at the close of the nineteenth century.” During that earlier period, the conditions that fostered modern storminess were apparently overpowered by something even more potent; i.e., cold temperatures, which the authors say led to an expansion of sea ice in the Greenland Sea that expanded and intensified the Greenland anticyclone, which in turn led to the North Atlantic cyclone track being displaced farther south. Additional support for this view is provided by the hypothesis of Clarke *et al.* (2002), who postulated that a southward spread of sea ice and polar water results in an increased thermal gradient between 50°N and 65°N that intensifies storm activity in the North Atlantic and supports dune formation in the Aquitaine region of southwest France.

These studies suggest the increased storminess and wave heights observed in the European sector of the North Atlantic Ocean over the past two decades are not the result of global warming, but rather are associated with the most recent periodic increase in the NAO index. A longer historical perspective reveals North Atlantic storminess was even more severe than it is now during the latter part of the nineteenth century, when it was significantly colder than it is now. The storminess of that much colder period was so great it was actually decoupled from the NAO index. Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Tide-gauge data also have been utilized as proxies for storm activity in England. Based on high-water measurements made at the Liverpool waterfront over the period 1768–1999, Woodworth and Blackman (2002) found the annual maximum surge-at-high-water declined at a rate of 0.11 ± 0.04 meters per century, suggesting the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (colder Little Ice Age) than the latter part (Current Warm Period).

Focusing on a well-studied and data-rich 16-km-long section of the Sefton coastline of northwest England, Esteves *et al.* (2011) used the longest available measured datasets from the eastern Irish Sea and beyond—including tide levels, surge heights, wind speeds, and wave heights—in a search for evidence of long-term changes in the metocean climate. They analyzed data defining the rate of change in shoreline position at the study site derived

from a range of historical maps and aerial photographs for the period 1894–2005, with the primary aim of assessing “whether temporal changes in the rates and magnitudes of coastal erosion can be attributed to the observed trends in metocean data, and if these trends can, in turn, be associated with climate change.”

According to the three UK researchers, their results “show no evidence of enhanced storminess or increases in surge heights or extreme water levels,” and “the evolution of the coastline analyzed at various temporal scales shows no strong connection with metocean trends.” With the exception of mean monthly wind speed (which trended slightly upwards at one site and slightly downwards at another), the authors report the available metocean data “do not indicate any statistically significant changes outside seasonal and decadal cycles.”

Dawson *et al.* (2004a) examined the sedimentary characteristics of a series of Late Holocene coastal windstorm deposits found on the Scottish Outer Hebrides, an island chain that extends across the latitudinal range 56–58°N. These deposits form part of the landward edges of coastal sand accumulations that are intercalated with peat, the radiocarbon dating of which was used to construct a local chronology of the windstorms. This work revealed “the majority of the sand units were produced during episodes of climate deterioration both prior to and after the well-known period of Medieval warmth.” The researchers also say “the episodes of sand blow indicated by the deposits may reflect periods of increased cyclogenesis in the Atlantic associated with increased sea ice cover and an increase in the thermal gradient across the North Atlantic region.” In addition, they report “dated inferred sand drift episodes across Europe show synchronicity with increased sand mobilization in SW France, NE England, SW Ireland and the Outer Hebrides, implying a regional response to storminess with increased sand invasion during the cool periods of the Little Ice Age,” citing the corroborative studies of Lamb (1995), Wintle *et al.* (1998), Gilbertson *et al.* (1999), and Wilson *et al.* (2001).

Dawson *et al.* (2004b) examined 120- to 225-year records of gale-days per year from five locations across Scotland, northwest Ireland, and Iceland, which they compared with a much longer 2,000-year record for the same general region. They found four of the five century-scale records showed a greater frequency of storminess in the cooler 1800s and early 1900s than throughout the remainder of the warmer twentieth century. “Considered over the last ca. 2000

years,” they report, “it would appear that winter storminess and climate-driven coastal erosion was at a minimum during the Medieval Warm Period,” just the opposite of what climate models typically predict; i.e., more storminess with warmer temperatures.

Throughout a vast portion of the North Atlantic Ocean and adjacent Europe, storminess and wind strength appear to have been inversely related to mean global air temperature over most of the past two millennia, with the most frequent and intense events occurring both prior to and following the Medieval Warm Period. The model-based claim that Europe will experience more intense and frequent windstorms if air temperatures continue to rise fails to resonate with reality.

Although some studies suggest there has been a recent increase in storminess across the United Kingdom, others have shown that as Earth has recovered from the global chill of the Little Ice Age, there has been no significant increase in either the frequency or intensity of stormy weather in this area. In fact, most studies suggest just the opposite.

References

Alexander, L.V., Tett, S.F.B., and Jonsson, T. 2005. Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophysical Research Letters* **32**: 10.1029/2005GL022371.

Allan, R., Tett, S., and Alexander, L. 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**: 357–371.

Clarke, M., Rendell, H., Tastet, J-P., Clave, B., and Masse, L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. *The Holocene* **12**: 231–238.

Dawson, A., Elliott, L., Noone, S., Hickey, K., Holt, T., Wadhams, P., and Foster, I. 2004b. Historical storminess and climate ‘see-saws’ in the North Atlantic region. *Marine Geology* **210**: 247–259.

Dawson, A.G., Hickey, K., Holt, T., Elliott, L., Dawson, S., Foster, I.D.L., Wadhams, P., Jonsdottir, I., Wilkinson, J., McKenna, J., Davis, N.R., and Smith, D.E. 2002. Complex North Atlantic Oscillation (NAO) Index signal of historic North Atlantic storm-track changes. *The Holocene* **12**: 363–369.

Dawson, S., Smith, D.E., Jordan, J., and Dawson, A.G. 2004a. Late Holocene coastal sand movements in the Outer Hebrides, N.W. Scotland. *Marine Geology* **210**: 281–306.

Esteves, L.S., Williams, J.J., and Brown, J.M. 2011.

Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Sciences* **11**: 1641–1656.

Gilbertson, D.D., Schwenninger, J.L., Kemp, R.A., and Rhodes, E.J. 1999. Sand-drift and soil formation along an exposed North Atlantic coastline: 14,000 years of diverse geomorphological, climatic and human impacts. *Journal of Archaeological Science* **26**: 439–469.

Lamb, H.H. 1995. *Climate, History and the Modern World*. Routledge, London, UK.

Wilson, P., Orford, J.D., Knight, J., Bradley, S.M., and Wintle, A.G. 2001. Late Holocene (post-4000 yrs BP) coastal development in Northumberland, northeast England. *The Holocene* **11**: 215–229.

Wintle, A.G., Clarke, M.L., Musson, F.M., Orford, J.D., and Devoy, R.J.N. 1998. Luminescence dating of recent dune formation on Inch Spit, Dingle Bay, southwest Ireland. *The Holocene* **8**: 331–339.

Woodworth, P.L. and Blackman, D.L. 2002. Changes in extreme high waters at Liverpool since 1768. *International Journal of Climatology* **22**: 697–714.

7.7.1.2.3 Other Regions

Bielec (2001) analyzed thunderstorm data from Cracow, Poland, for the period 1896–1995, finding an average of 25 days of such activity per year, with a non-significant linear-regression-derived increase of 1.6 storm days from the beginning to the end of the record. From 1930 onward, the trend was negative, revealing a similarly derived decrease of 1.1 storm days. In addition, there was a decrease in the annual number of thunderstorms with hail over the entire period and a decrease in the frequency of storms producing precipitation in excess of 20 mm.

Similar findings were reported by the same author two years later (Bielec-Bakowska, 2003) for thunderstorm occurrences at seven Polish synoptic weather stations (Hel, Szczecin, Koszalin, Poznan, Wroclaw, Raciborz, and Krakow) over the period 1885–2000. In this second study the University of Silesia scientist determined “over an annual period of 116 years, no clear trends of changes in the number of days with thunderstorms in Poland were found,” noting also “interannual variability of days with thunderstorms in individual seasons did not show any specific trend,” except in the winter season, and then only for Szczecin, Krakow, and Koszalin. These findings led her to state “the analysis did not unequivocally confirm the opinion that the number of

Observations: Extreme Weather

thunderstorms in the cold part of the year increases,” and “a similar phenomenon was observed in the whole of Europe.”

With the perspective of anthropogenic climate change, Barring and von Storch (2004) point out, the occurrence of extreme events such as windstorms may “create the perception that ... the storms lately have become more violent, a trend that may continue into the future.” Intending to test this inference, and relying on data rather than perception to address the topic, the two researchers analyzed long time series of pressure readings for Lund (since 1780) and Stockholm (since 1823), Sweden, analyzing the annual number of pressure observations below 980 hPa, the annual number of absolute pressure tendencies exceeding 16 hPa/12h, and intra-annual 95th and 99th%iles of the absolute pressure differences between two consecutive observations. They determined the storminess time series they developed “are remarkably stationary in their mean, with little variations on time scales of more than one or two decades.” For example, they note “the 1860s–70s was a period when the storminess indices showed general higher values,” as was the 1980s–1990s, but subsequently, “the indices have returned to close to their long-term mean.”

Barring and von Storch conclude their storminess proxies “show no indication of a long-term robust change towards a more vigorous storm climate.” During “the entire historical period,” storminess was “remarkably stable, with no systematic change and little transient variability.”

Noting “a great amount of evidence for changing storminess over northwestern Europe is based on indirect data and reanalysis data rather than on station wind data,” Smits *et al.* (2005) investigated trends in storminess over the Netherlands based on hourly records of 10-m wind speed observations made at 13 meteorological stations across the country with uninterrupted records for the time period 1962–2002. They report “results for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands [of] between 5 and 10% per decade.”

Raichich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, to determine historical trends of surges and anomalies. This work revealed no definite trends in weak and moderate positive surges, while strong positive surges clearly became less frequent, even in the face of a gradually

rising sea level, “presumably,” in the words of Raichich, “as a consequence of a general weakening of the atmospheric activity,” also found to have been the case for Brittany (France) by Pirazzoli (2000).

Barredo (2010) examined large historical windstorm event losses in Europe over the period 1970–2008 for 29 European countries. After adjusting the data for “changes in population, wealth, and inflation at the country level and for inter-country price differences using purchasing power parity,” the researcher, employed by the Institute for Environment and Sustainability, European Commission-Joint Research Centre in Ispra, Italy, reported “the analyses reveal no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure,” adding “increasing disaster losses are overwhelmingly a consequence of changing societal factors.”

Additional evidence for the recent century-long decrease in storminess in and around Europe comes from Bijl *et al.* (1999), who analyzed long-term sea-level records from several coastal stations in northwest Europe. They report, “although results show considerable natural variability on relatively short (decadal) time scales,” there is “no sign of a significant increase in storminess ... over the complete time period of the data sets.” In the southern portion of the North Sea, where natural variability was more moderate, they found a trend, but it was “a tendency towards a weakening of the storm activity over the past 100 years.”

Stoffel *et al.* (2005) note debris flows are a type of mass movement that frequently causes major destruction in alpine areas; since 1987, they report, there had been an apparent above-average occurrence of such events in the Valais region of the Swiss Alps, prompting some researchers to suggest the increase was the result of global warming (Rebetez *et al.*, 1997). Stoffel *et al.* used dendrochronological methods to determine whether the recent increase in debris-flow events was indeed unusual, and if so whether it made sense to attribute the increase to CO₂-induced global warming.

In extending the history of debris-flow events (1922–2002) back to the year 1605, they found “phases with accentuated activity and shorter recurrence intervals than today existed in the past, namely after 1827 and until the late nineteenth century.” The nineteenth century period of high-frequency debris flow was shown to coincide with a period of higher flood activity in major Swiss rivers, and less frequent debris flow activity after 1922

corresponded with lower flooding frequencies. Debris flows from extremely large mass movement events, similar to what occurred in 1993, were found to have “repeatedly occurred” in the historical past, and to have been of such substantial magnitude that, in the opinion of Stoffel *et al.*, the “importance of the 1993 debris-flow surges has to be thoroughly revised.”

Stoffel *et al.*’s work demonstrates the apparent above-average number of debris flow events since 1987 was only that—apparent. They report debris flows occurred “ever more frequently in the nineteenth century than they do today.” They conclude, “correlations between global warming and modifications in the number or the size of debris-flow events, as hypothesized by, e.g., Haeberli and Beniston (1998), cannot, so far, be confirmed in the study area.”

These findings clearly demonstrate the importance of evaluating the uniqueness of Earth’s contemporary climatic state—or the uniqueness of recent trends in various climate-related phenomena—over a much longer timespan than just the past century or, even worse, merely a portion of it. Only when a multicentennial or millennial view of the subject is available can one adequately evaluate the uniqueness of a climate-related phenomenon’s recent behavior, let alone link that behavior to late twentieth century or early twenty-first century global warming.

Other studies reveal important conclusions with respect to trends in storminess when examining a timescale much longer than 100 years. Ogrin (2007) presented “an overview of severe storms and a reconstruction of periods with their reiterative occurrence in sub-Mediterranean Slovenia in the warm half of the year during the so-called pre-instrumental period,” based on “data gathered in secondary and tertiary historical sources.” Speaking of “violent storms” and “the periods in which these phenomena were more frequent and reached, as to the costs of damage caused, the level of natural disasters or even catastrophes,” Ogrin reports “the 17th and 18th centuries were undoubtedly such periods, particularly their first halves, when besides storms also some other weather-caused natural disasters occurred quite often, so that the inhabitants, who mainly depended on the self-subsistent agriculture, could not recover for several years after some consecutive severe rigours of the weather.” In addition, he reports “the frequency of violent storms in that time was comparable to the incidence towards the end of the 20th century.”

Ogrin, who is in the Department of Geography of

the University of Ljubljana, writes the late twentieth century increase in violent storms “is supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere.” However, he reports “the damage done by severe storms in the past does not differ significantly from the damage in the present.” This suggests the weather extremes of today, which he says are “supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere,” may in fact be caused by something else, for if they have occurred in the past for a different reason (and they have), they can be occurring today for a different reason too.

Clarke and Rendell (2009) also recognized “an understanding of the patterns of past storminess is particularly important in the context of future anthropogenically driven climate change,” especially in light of “predictions of increased storm frequency ... by the end of the current century.” They reviewed evidence for storm activity across the North Atlantic region derived from instrumental records and archival evidence of storm impacts, which they then compared to sedimentological and chronological evidences of sand movement and dune building along western European coasts.

The two UK researchers determined “the most notable Aeolian sand drift activity was concentrated in the historic period 0.5–0.1 ka (AD 1500–1900) which spans the Little Ice Age.” They state “within this period, low solar activity, during the Maunder (AD 1645–1715) and Dalton (AD 1790–1830) Minima, has been related to changes in Atlantic storm tracks (van der Schrier and Barkmeijer, 2005), anomalously cold winter and summer temperatures in Scandinavia (Bjerknes, 1965), and the repositioning of the polar front and changing sea ice cover (Ogilvie and Jonsson, 2001).” In addition, they state “the Holocene record of sand drift in western Europe includes episodes of movement corresponding to periods of Northern Hemisphere cooling (Bond *et al.*, 1997) ... and provides the additional evidence that these periods, like the Little Ice Age, were also stormy,” further suggesting any future global warming would more likely result in less, rather than more, storminess in that part of the planet.

Based on optically stimulated luminescence (OSL) dating of the coastal sediment succession, Riemann *et al.* (2011) established “a detailed and reliable chronology” of the Swina barrier at the southern end of the Baltic Sea, two sandy spits or

Observations: Extreme Weather

depositional landforms (Wolin and Uznam) that extend outward from the seacoast. This sediment history revealed much about the climate history of the region. Following the Roman Warm Period, which the five researchers say “is known for a moderate and mild climate in Europe” that produced brown foredunes, there was a hiatus between the brown and yellow dunes from 470 AD to 760 AD that “correlates with a cold and stormy period that is known as the Dark Ages Cold Period,” which they say “is well known as a cooling event in the climatic records of the North Atlantic (Bond *et al.*, 1997; McDermott *et al.*, 2001) and in marine sediment cores from Skagerrak (Hass, 1996),” and which also was associated with a phase of increased aeolian activity in northeast England reported by Wilson *et al.* (2001).

Next, as expected, came the Medieval Warm Period. And finally, Riemann *et al.* write, “the cold and stormy Little Ice Age (Hass, 1996) correlates to the formation of the transgressive white dune I in the sediment successions, which were dated to between 1540 and 1660 AD.” They note, “the Little Ice Age is documented in North and West Europe in plenty of coastal dunefields, and resulted in sand mobilisation and development of transgressive dunes (e.g., Clemmensen *et al.*, 2001a,b, 2009; Wilson *et al.*, 2001, 2004; Clarke *et al.*, 2002; Ballarini *et al.*, 2003; Clemmensen and Murray, 2006; Aagaard *et al.*, 2007; Sommerville *et al.*, 2007; Clarke and Rendell, 2009),” due to a colder climate and increased storminess related to periodic shifts of the North Atlantic Oscillation (Dawson *et al.*, 2002).

Noting “the systematic accretion of foredunes is accompanied by a moderate climate and a progressive plant cover,” the German and Polish scientists say foredune instability is “related to aeolian sand mobilisation within phases of a decreased plant cover caused by colder and stormier conditions.” These numerous sets of dune-derived data clearly demonstrate that in this particular part of the world warming brings less storminess.

Remarking that “the Mediterranean region is one of the world’s most vulnerable areas with respect to global warming,” citing Giorgi (2006), Sabatier *et al.* (2012) produced a high-resolution record of paleostorm events along the French Mediterranean coast over the past 7,000 years. According to the nine French scientists, their work “recorded seven periods of increased storm activity at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400, and 400–50 cal yr BP.” They associate the latter interval with the Little Ice Age. “In contrast,” they state, their

results show “the Medieval Climate Anomaly (1150–650 cal yr BP) was characterized by low storm activity.” In addition, they note these changes in coastal hydrodynamics were in phase with those observed over the Eastern North Atlantic by Billeaud *et al.* (2009) and Sorrel *et al.* (2009), and the periods of increased storminess they identified seem to correspond to periods of Holocene cooling detected in the North Atlantic by Bond *et al.* (1997, 2001), together with decreases in sea surface temperature reported by Berner *et al.* (2008), who they also say “associated this high frequency variation in sea surface temperature with ^{14}C production rates, implying solar-related changes are an important underlying mechanism for the observed ocean climate variability.”

Sabatier *et al.* conclude “whatever the ultimate cause of these millennial-scale Holocene climate variations, the main decreases of sea surface temperature observed in the North Atlantic seem to be an important mechanism to explain high storm activity in the NW Mediterranean area.” Their together with those of the others they cite, suggest if Earth’s climate continues to warm, for whatever reason, storm activity in the Northwest Mediterranean area will likely significantly subside.

Barring and Fortuniak (2009) point out “extra-tropical cyclone frequency and intensity are currently under intense scrutiny because of the destruction recent windstorms have brought to Europe.” They note “several studies using reanalysis data covering the second half of the 20th century suggest increasing storm intensity in the northeastern Atlantic and European sector.” They analyzed the “inter-decadal variability in cyclone activity over northwestern Europe back to AD 1780 by combining information from eight storminess indices applied in a Eulerian framework,” indices that “use the series of thrice-daily sea level pressure observations at Lund and Stockholm” in Scandinavia.

The two Swedish scientists say their results show former reanalysis studies “cover a time period chiefly coinciding with a marked, but not exceptional in our 225-year perspective, positive variation in the regional cyclone activity that has more recently reversed,” noting “because of the inter-decadal variations, a near-centennial time perspective is needed when analyzing variations in extra-tropical cyclone activity and the associated weather conditions over northwestern Europe.” By taking this more long-term approach, the two researchers found “there is no significant overall long-term trend common to all

indices in cyclone activity in the North Atlantic and European region since the Dalton minimum”; “the marked positive trend beginning around 1960 ended in the mid-1990s and has since then reversed”; and “this positive trend was more an effect of a 20th-century minimum in cyclone activity around 1960, rather than extraordinary high values in [the] 1990s.”

Clemmensen *et al.* (2007) examined sedimentological and geomorphological properties of the dune system on the Danish island of Anholt, finding “the last aeolian activity phase on Anholt (AD 1640–1900) is synchronous with the last part of the Little Ice Age.” The team of researchers further note “dune stabilization on Anholt seems to a large degree to have been natural, and probably records a decrease in storminess at the end of the 19th century and the beginning of the 20th century,” and this timing “is roughly simultaneous with dunefield stabilization on the west coast of Jutland and on Skagen Odde,” citing the work of Clemmensen and Murray (2006).

Bjorck and Clemmensen (2004) extracted cores of peat from two raised bogs in the near-coastal part of southwest Sweden, from which they derived histories of wind-transported clastic material via systematic counts of quartz grains of various size classes that enabled them to calculate temporal variations in Aeolian Sand Influx (ASI), which has been shown to be correlated with winter wind climate in that part of the world. They found “the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia.” Specifically, “decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks,” and “centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters.”

The two researchers also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 “is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here.” In addition, they state an event of increased storminess they dated to AD 1650 “falls at the beginning of the Maunder

solar minimum (AD 1645–1715).” They also find high ASI values between AD 1450 and 1550 with “a very distinct peak at AD 1475,” noting this period coincides with the Sporer Minimum of AD 1420–1530. In addition, they note the latter three peaks in winter storminess all occurred during the Little Ice Age and “are among the most prominent in the complete record.”

The two researchers also report degree of humification (DOH) intervals “correlate well with the classic late-Holocene climatic intervals,” which they specifically state to include the Modern Climate Optimum (100–0 cal. yr BP), the Little Ice Age (600–100 cal. yr BP), the Medieval Warm Period (1250–600 cal. yr BP), the Dark Ages Cold Period (1550–1250 cal. yr BP), and the Roman Climate Optimum (2250–1550 cal. yr BP). There would thus appear to be little doubt that winter storms throughout southern Scandinavia were more frequent and intense during the multicentury Dark Ages Cold Period and Little Ice Age than during the Roman Warm Period, Medieval Warm Period, and Current Warm Period, providing strong evidence to refute the contention that storminess tends to increase during periods of greater warmth.

As Earth has recovered from the global chill of the Little Ice Age, there appears to have been no significant increase in either the frequency or intensity of stormy weather in many regions across Europe. Most studies suggest just the opposite. There is no real-world or data-driven reason to believe storms would necessarily get any worse or become more frequent if Earth were to warm somewhat more in the future.

References

- Aagaard, T., Orford, J., and Murray, A.S. 2007. Environmental controls on the coastal dune formation; Skallingen Spit, Denmark. *Geomorphology* **83**: 29–47.
- Ballarini, M., Wallinga, J., Murray, A.S., van Heteren, S., Oost, A.P., Bos, A.J.J., and van Eijk, C.W.E. 2003. Optical dating of young coastal dunes on a decadal time scale. *Quaternary Science Reviews* **22**: 1011–1017.
- Barredo, J.I. 2010. No upward trend in normalized windstorm losses in Europe: 1970–2008. *Natural Hazards and Earth System Sciences* **10**: 97–104.
- Barring, L. and Fortuniak, K. 2009. Multi-indices analysis of southern Scandinavian storminess 1780–2005 and links to interdecadal variations in the NW Europe-North Sea region. *International Journal of Climatology* **29**: 373–384.

Observations: Extreme Weather

- Barring, L. and von Storch, H. 2004. Scandinavian storminess since about 1800. *Geophysical Research Letters* **31**: 10.1029/2004GL020441.
- Berner, K.S., Koc, N., Divine, D., Godtliessen, F., and Moros, M. 2008. A decadal-scale Holocene sea surface temperature record from the subpolar North Atlantic constructed using diatoms and statistics and its relation to other climate parameters. *Paleoceanography* **23**: 10.1029/2006PA001339.
- Bielec, Z. 2001. Long-term variability of thunderstorms and thunderstorm precipitation occurrence in Cracow, Poland, in the period 1896-1995. *Atmospheric Research* **56**: 161–170.
- Bielec-Bakowska, Z. 2003. Long-term variability of thunderstorm occurrence in Poland in the 20th century. *Atmospheric Research* **67**: 35–52.
- Bijl, W., Flather, R., de Ronde, J.G., and Schmith, T. 1999. Changing storminess? An analysis of long-term sea level data sets. *Climate Research* **11**: 161–172.
- Billeaud, I., Tessier, B., and Lesueur, P. 2009. Impacts of the Holocene rapid climate change as recorded in a macrotidal coastal setting (Mont-Saint-Michel Bay, France). *Geology* **37**: 1031–1034.
- Bjerknes, J. 1965. Atmospheric-ocean interaction during the ‘Little Ice Age.’ In: WMO-IUGG Symposium on Research and Development Aspects of Long-Range Forecasting, WMO-No. 162, TP 79, Technical Note 66, pp. 77–88.
- Bjorck, S. and Clemmensen, L.B. 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene* **14**: 677–688.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Bond, G., Showers, W., Chezebiet, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G. 1997. A pervasive millennial scale cycle in North-Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.
- Clarke, M.L. and Rendell, H.M. 2009. The impact of North Atlantic storminess on western European coasts: a review. *Quaternary International* **195**: 31–41.
- Clarke, M., Rendell, H., Tastet, J.-P., Clave, B., and Masse, L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. *The Holocene* **12**: 231–238.
- Clemmensen, L.B., Bjornsen, M., Murray, A., and Pedersen, K. 2007. Formation of Aeolian dunes on Anholt, Denmark since AD 1560: A record of deforestation and increased storminess. *Sedimentary Geology* **199**: 171–187.
- Clemmensen, L.B. and Murray, A. 2006. The termination of the last major phase of aeolian sand movement, coastal dunefields, Denmark. *Earth Surface Processes and Landforms* **31**: 795–808.
- Clemmensen, L.B., Murray, A., Beck, J.H., and Clausen, A. 2001b. Large-scale aeolian sand movement on the west coast of Jutland, Denmark in late Subboreal to early Subatlantic time—a record of climate change or cultural impact? *Geologiska Foreningens i Stockholm Forhandlingar* **123**: 193–203.
- Clemmensen, L.B., Murray, A., Heinemeier, J., and de Jong, R. 2009. The evolution of Holocene coastal dunefields, Jutland, Denmark: a record of climate change over the past 5000 years. *Geomorphology* **105**: 303–313.
- Clemmensen, L.B., Pye, K., Murray, A., and Heinemeier, J. 2001a. Sedimentology, stratigraphy, and landscape evolution of a Holocene coastal dune system, Lodbjerg, NW Jutland, Denmark. *Sedimentology* **48**: 3–27.
- Dawson, A.G., Hickey, K., Holt, T., Elliott, L., Dawson, S., Foster, I.D.L., Wadhams, P., Jonsdottir, I., Wilkinson, J., McKenna, J., Davis, N.R., and Smith, D.E. 2002. Complex North Atlantic Oscillation (NAO) index signal of historic North Atlantic storm-track changes. *The Holocene* **12**: 363–369.
- Giorgi, F. 2006. Climate change hot-spots. *Geophysical Research Letters* **33**: 10.1029/2006GL025734.
- Haeberli, W. and Beniston, M. 1998. Climate change and its impacts on glaciers and permafrost in the Alps. *Ambio* **27**: 258–265.
- Hass, H.C. 1996. Northern Europe climate variations during late Holocene: evidence from marine Skagerrak. *Palaeogeography, Palaeoclimatology, Palaeoecology* **123**: 121–145.
- McDermott, F., Mathey, D.P., and Hawkesworth, C. 2001. Centennial-scale Holocene climate variability revealed by a high-resolution speleothem ¹⁸O record from SW Ireland. *Science* **294**: 1328–1331.
- Ogilvie, A.E.J. and Jonsson, T. 2001. “Little Ice Age” research: a perspective from Iceland. *Climatic Change* **48**: 9–52.
- Ogrin, D. 2007. Severe storms and their effects in sub-Mediterranean Slovenia from the 14th to the mid-19th century. *Acta Geographica Slovenia* **47**: 7–24.
- Pirazzoli, P.A. 2000. Surges, atmospheric pressure and wind change and flooding probability on the Atlantic coast of France. *Oceanologica Acta* **23**: 643–661.

Raichich, F. 2003. Recent evolution of sea-level extremes at Trieste (Northern Adriatic). *Continental Shelf Research* **23**: 225–235.

Rebetez, M., Lugon, R., and Baeriswyl, P.-A. 1997. Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps). *Climatic Change* **36**: 371–389.

Reimann, T., Tsukamoto, S., Harff, J., Osadczuk, K., and Frechen, M. 2011. Reconstruction of Holocene coastal foredune progradation using luminescence dating—An example from the Swina barrier (southern Baltic Sea, NW Poland). *Geomorphology* **132**: 1–16.

Sabatier, P., Dezileau, L., Colin, C., Briquet, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O., and Von Grafenstein, U. 2012. 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events. *Quaternary Research* **77**: 1–11.

Smits, A., Klein Tank, A.M.G., and Konnen, G.P. 2005. Trends in storminess over the Netherlands, 1962–2002. *International Journal of Climatology* **25**: 1331–1344.

Sommerville, A.A., Hansom, J.D., Housley, R.A., and Sanderson, D.C.W. 2007. Optically stimulated luminescence (OSL) dating of coastal aeolian sand accumulation in Sanday, Orkney Islands, Scotland. *The Holocene* **17**: 627–637.

Sorrel, P., Tessier, B., Demory, F., Delsinne, N., and Mouaze, D. 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). *Quaternary Science Reviews* **28**: 499–516.

Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gärtner, H.W., and Monbaron, M. 2005. 400 years of debris-flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. *Arctic, Antarctic, and Alpine Research* **37**: 387–395.

van der Schrier, G. and Barkmeijer, J. 2005. Bjerknes' hypothesis on the coldness during AD 1790–1820 revisited. *Climate Dynamics* **24**: 355–371.

Wilson, P., McGourty, J., and Bateman, M.D. 2004. Mid-to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. *The Holocene* **14**: 406–416.

Wilson, P., Orford, J.D., Knight, J., Braley, S.M., and Wintle, A.G. 2001. Late-Holocene (post-4000 years BP) coastal dune development in Northumberland, northeast England. *The Holocene* **11**: 215–229.

7.7.1.3 North America

7.7.1.3.1 Canada

Recognizing “media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe weather events,” Hage (2003) set out to test this hypothesis in the prairie provinces of Alberta and Saskatchewan in western Canada. The author utilized “previously unexploited written resources such as daily and weekly newspapers and community histories” to establish a database adequate for determining long-term trends of all destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) for the region over the period 1882–2001. Hage notes because “sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns, ... extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors.” Hage found “all intense storms showed no discernible changes in frequency after 1940.”

Lawson (2003) examined the occurrence of blizzards at a number of locations within the Prairie Ecozone of western Canada, analyzing trends in occurrence and severity over the period 1953–1997. No significant trends were found in central and eastern locations. In the western prairie locations, the author found a significant downward trend in blizzard frequency, noting “this trend is consistent with results found by others that indicate a decrease in cyclone frequency over western Canada.” He also notes the blizzards that do occur “exhibit no trend in the severity of their individual weather elements.” These observed trends “serve to illustrate that the changes in extreme weather events anticipated under Climate Change may not always be for the worse.”

Gascon *et al.* (2010) conducted a study they describe as “the first to document the climatology of major cold-season precipitation events that affect southern Baffin Island.” They examined the characteristics and climatology of the 1955–2006 major cold-season precipitation events at Iqaluit, the capital of Nunavut, located on the southeastern part of Baffin Island in the northwestern end of Frobisher Bay, basing their work on analyses of hourly surface meteorological data obtained from the public archives

Observations: Extreme Weather

of Environment Canada. The precipitation data were corrected to account for gauge catchment errors due to wind effects, snow-water equivalence variations, and human error in the manually retrieved precipitation data for the period 1955–1996; the remaining data were used in their uncorrected state.

The three researchers detected a non-significant decrease in autumn and winter storm activity over the period of their study, which they say comports with the results of Curtis *et al.* (1998), who observed a concomitant decrease in annual precipitation in the western Arctic. This was true in spite of the findings of Zhang *et al.* (2004), who Curtis *et al.* say “reported an increase in cyclonic activity over the past fifty years, as well as McCabe *et al.* (2001), Wang *et al.* (2004) and Yin (2005),” who reported a northward shift in such activity. That shift apparently was not great enough to “translate into major precipitation events, or at least not in Iqaluit,” as revealed by the authors’ results depicted in Figure 7.7.1.3.1.1.

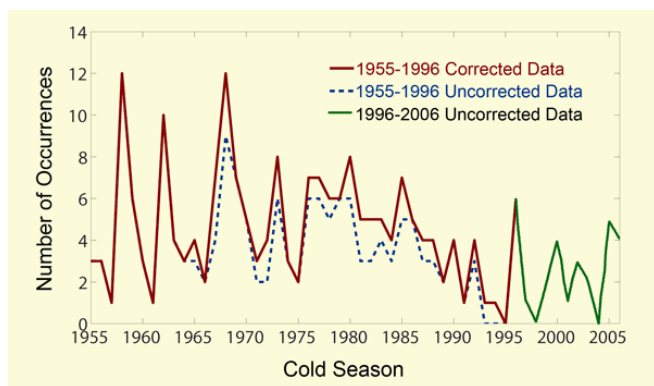


Figure 7.7.1.3.1.1. Cold-season occurrences of major precipitation events at Iqaluit, Nunavut, Canada. Adapted from Gascon, G., Stewart, R.E., and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327–337.

References

Curtis, J., Wendler, G., Stone, R., and Dutton, E. 1998. Precipitation decrease in the western Arctic, with special emphasis on Barrow and Barter Island, Alaska. *International Journal of Climatology* **18**: 1687–1707.

Gascon, G., Stewart, R.E., and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327–337.

Hage, K. 2003. On destructive Canadian prairie windstorms and severe winters. *Natural Hazards* **29**: 207–228.

Lawson, B.D. 2003. Trends in blizzards at selected locations on the Canadian prairies. *Natural Hazards* **29**: 123–138.

McCabe, G.J., Clark, M.P., and Serreze, M.C. 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. *Journal of Climate* **14**: 2763–2768.

Wang, X.L., Swail, V.R., and Zwiers, F.W. 2004. Changes in extratropical storm tracks and cyclone activity as derived from two global reanalyses and the Canadian CGCM2 projections of future climate. *Eighth International Workshop on Wave Hindcasting and Forecasting, 14–19 November 2004, Oahu, Hawaii*. Environment Canada, Paper B1.

Yin, J.H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters* **32**: 10.1029/2005GL023684.

Zhang, X., Walsh, J.E., Zhang, J., Bhatt, U.S., and Ikeda, M. 2004. Climatology and interannual variability of Arctic cyclone activity: 1948–2002. *Journal of Climate* **17**: 2300–2317.

7.7.1.3.2 Alaska

Hudak and Young (2002) examined the number of fall (June–November) storms in the southern Beaufort Sea region based on criteria of surface wind speed for the relatively short period of 1970–1995. Although there was considerable year-to-year variability in the number of storms, there was no discernible trend over the 26-year period in this region of the globe, where climate models predict the effects of CO₂-induced global warming to be most evident.

Mason and Jordan (2002) studied numerous depositional environments along the tectonically stable, unglaciated eastern Chuckchi Sea coast that stretches across northwest Alaska, deriving a 6,000-year record of sea-level change. They learned “in the Chukchi Sea, storm frequency is correlated with colder rather than warmer climatic conditions.” Consequently, they say their data “do not therefore support predictions of more frequent or intense coastal storms associated with atmospheric warming for this region.”

References

Hudak, D.R. and Young, J.M.C. 2002. Storm climatology of the southern Beaufort Sea. *Atmosphere-Ocean* **40**: 145–158.

Mason, O.W. and Jordan, J.W. 2002. Minimal late

Holocene sea level rise in the Chukchi Sea: Arctic insensitivity to global change? *Global and Planetary Changes* **32**: 13–23.

7.7.1.3.3 Eastern USA

Zhang *et al.* (2000) used ten long-term records of storm surges derived from hourly tide gauge measurements to calculate annual values of the number, duration, and integrated intensity of storms in this region. Their analysis did not reveal any trends in storm activity during the twentieth century, which they say is suggestive of “a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr.”

Similar results were reported by Boose *et al.* (2001), who examined historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They discerned “no clear century-scale trend in the number of major hurricanes.” For the most recent and reliable 200-year portion of the record, however, the cooler nineteenth century had five of the highest-damage F3 category storms, whereas the warmer twentieth century had only one such storm.

Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration’s Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York between 1851 and 2005 to assess the degree of likelihood that twentieth century global warming might be influencing these storms. According to the author, “a total of 76 storms of tropical origin passed over New York State between 1851 and 2005,” and of these storms, “14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms.” For Long Island in particular, he further reports “the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively.” He found storm activity was greatest in the late nineteenth century and late twentieth century, and “the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century.” Vermette thus concludes, “rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century.”

Noren *et al.* (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km² region of Vermont and eastern New York. They found “the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr.” The most recent upswing in storminess did not begin with what the IPCC calls the unprecedented warming of the twentieth century, but “at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age.” The authors conclude the increase in storminess was likely a product of natural changes in the Arctic Oscillation.

Mallinson *et al.* (2011) employed optically stimulated luminescence (OSL) dating of inlet-fill and flood tide delta deposits from locations in the Outer Banks barrier islands of North Carolina to provide a “basis for understanding the chronology of storm impacts and comparison to other paleoclimate proxy data” in the region over the past 2,200 years. Analyses of the cores revealed “the Medieval Warm Period (MWP) and Little Ice Age (LIA) were both characterized by elevated storm conditions as indicated by much greater inlet activity relative to today.” They write, “given present understanding of atmospheric circulation patterns and sea-surface temperatures during the MWP and LIA, we suggest that increased inlet activity during the MWP responded to intensified hurricane impacts, while elevated inlet activity during the LIA was in response to increased nor’easter activity.” The group of five researchers state their data indicate, relative to climatic conditions of the Medieval Warm Period and Little Ice Age, there has more recently been “a general decrease in storminess at mid-latitudes in the North Atlantic,” reflecting “more stable climate conditions, fewer storm impacts (both hurricane and nor’easter), and a decrease in the average wind intensity and wave energy field in the mid-latitudes of the North Atlantic.”

References

- Boose, E.R., Chamberlin, K.E., and Foster, D.R. 2001. Landscape and regional impacts of hurricanes in New England. *Ecological Monographs* **71**: 27–48.
- Mallinson, D.J., Smith, C.W., Mahan, S., Culver, S.J., and McDowell, K. 2011. Barrier island response to late Holocene climate events, North Carolina, USA. *Quaternary Research* **76**: 46–57.
- Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., and

Observations: Extreme Weather

Southon, J. 2002. Millennial-scale storminess variability in the northeastern United States during the Holocene epoch. *Nature* **419**: 821–824.

Vermette, S. 2007. Storms of tropical origin: a climatology for New York State, USA (1851–2005). *Natural Hazards* **42**: 91–103.

Zhang, K., Douglas, B.C., and Leatherman, S.P. 2000. Twentieth-Century storm activity along the U.S. East Coast. *Journal of Climate* **13**: 1748–1761.

7.7.1.3.4 Central and Southern USA

Bove *et al.* (1998) studied land-falling hurricanes whose eyes crossed the coast between Cape Sable, Florida and Brownsville, Texas between 1896 and 1995, finding the first half of the twentieth century had more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. The same is true for intense hurricanes of category 3 on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes have been trending downward since 1966, with the decade starting in 1986 exhibiting the fewest intense hurricanes of the century.

Liu and Fearn (1993) studied major storms along the U.S. Gulf Coast over the past 3,500 years. Using sediment cores taken from the center of Lake Shelby in Alabama, they determined “major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years,” with the last of these superstorms occurring around 700 years ago. They further note “climate modeling results based on scenarios of greenhouse warming predict a 40%–50% increase in hurricane intensities in response to warmer tropical oceans.” If one of these severe storms (about a century overdue) were to hit the Alabama coast, it would be nothing more than an illustration of the age-old adage that history repeats itself.

Muller and Stone (2001) examined historical data relating to tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island, Texas to Cape Hatteras, North Carolina for the 100-year period 1901–2000. Their analysis revealed the temporal variability of tropical storm and hurricane strikes was “great and significant,” with most coastal sites experiencing “pronounced clusters of strikes separated by tens of years with very few strikes.” The data did not support the claim of a tendency for increased storminess during warmer El Niño years; for tropical storms and hurricanes together, the

authors found an average of 1.7 storms per El Niño season, 2.6 per neutral season, and 3.3 per La Niña season. For hurricanes only, the average rate of occurrence ranged from 0.5 per El Niño season to 1.7 per La Niña season.

Daoust (2003) suggested using tornado days instead of tornado frequencies “provides a more stable data set which should allow a more accurate analysis of the phenomenon.” Daoust catalogued daily tornado frequencies for each county of Missouri, USA, for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state’s 115 counties, its six climatic divisions, and the entire state. Results indicated the presence of positive trends in the tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant, but negative. At the state level, Daoust reports “for the last 53 years, no long-term trend in tornado days can be found.”

Changnon (2001) compared thunderstorm activity at both an urban and rural location in Chicago to determine whether there might be an urban influence on thunderstorm activity. Over the 40-year period investigated (1959–1998), he found the urban station experienced an average of 4.5 (12%) more thunderstorm days per year than the more rural station, and statistical tests revealed this difference to be significant at the 99% level in all four seasons of the year. This finding should elicit further caution in interpreting storm trend studies, many of which are based on data obtained from urban locations, which in the case of thunderstorms in Chicago, skewed the observational data upwards.

References

Bove, M.C., Zierden, D.F., and O’Brien, J.J. 1998. Are gulf landfalling hurricanes getting stronger? *Bulletin of the American Meteorological Society* **79**: 1327–1328.

Changnon, S.A. 2001. Assessment of historical thunderstorm data for urban effects: the Chicago case. *Climatic Change* **49**: 161–169.

Daoust, M. 2003. An analysis of tornado days in Missouri for the period 1950–2002. *Physical Geography* **24**: 467–487.

Liu, K.-b. and Fearn, M.L. 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* **21**: 793–796.

Muller, R.A. and Stone, G.W. 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast U.S. coast. *Journal of Coastal Research* 17: 949–956.

7.7.1.3.5 Conterminous USA

Hayden (1999) investigated storm frequencies between 25° and 55°N latitude and 60° and 125°W longitude from 1885 to 1996. Over this 112-year period, he reports, large regional changes in storm occurrences were observed, but when integrated over the entire geographic area, no net change in storminess was evident.

Similar results were noted by Changnon and Changnon (2000), who examined hail-day and thunder-day occurrences over the 100-year period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the country. They found the frequency of thunder-days peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Thereafter, both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence decreased to only 65% of what it was at mid-century, accompanied by a drop in national hail insurance losses over the same period.

Several years later, the authors conducted an analysis of snowstorms. Changnon and Changnon (2006) point out “global climate models predict that more weather extremes will be a part of a changed climate due to greenhouse gases,” and such a climate change “is anticipated to result in alterations of cyclone activity over the Northern Hemisphere (Lawson, 2003).” They also note “a change in the frequency, locations, and/or intensity of extratropical cyclones in the mid-latitudes would alter the incidence of snowstorms,” citing the work of Trenberth and Owen (1999).

The authors conducted “a climatological analysis of the spatial and temporal distributions of ... damaging snowstorms and their economic losses ... using property-casualty insurance data that consist of highly damaging storm events, classed as catastrophes by the insurance industry, during the 1949–2000 period.” In support of this approach to the subject, they report the National Academy of Sciences has identified insurance catastrophe data as “the nation’s best available loss data (National Research Council, 1999).”

The father-and-son research team reports “the

incidence of storms peaked in the 1976–1985 period,” but snowstorm incidence “exhibited no up or down trend during 1949–2000,” although national monetary losses did have a significant upward time trend indicative of “a growing societal vulnerability to snowstorms.” The two researchers conclude, “the temporal frequency of damaging snowstorms during 1949–2000 in the United States does not display any increase over time, indicating that either no climate change effect on cyclonic activity has begun, or if it has begun, altered conditions have not influenced the incidence of snowstorms.”

Schwartz and Schmidlin (2002) compiled a database of blizzards for the years 1959–2000 for the conterminous United States. A total of 438 blizzards were identified in the 41-year record, yielding an average of 10.7 blizzards per year. Year-to-year variability was significant, with the number of annual blizzards ranging from a low of 1 in the winter of 1980–1981 to a high of 27 during the winter of 1996–1997. Linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period; the total area affected by blizzards each winter remained relatively constant and showed no trend. If these observations are both correct, then average blizzard size is much smaller now than it was four decades ago. As the authors note, however, “it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States.”

The work of Schwartz and Schmidlin suggests the frequency of U.S. blizzards may have increased, but intensity likely decreased. Alternatively, the authors suggest the reported increase in blizzard frequency may be due to an observational bias that developed over the years, for which there is a known analogue in the historical observation of tornadoes. That this possibility is likely a probability is suggested by the study of Gulev *et al.* (2001), who analyzed trends in Northern Hemispheric winter cyclones over essentially the same time period (1958–1999) and found a statistically significant decline of 1.2 cyclones per year using NCEP/NCAR reanalysis pressure data.

Balling and Cervený (2003) reviewed the scientific literature to determine what has been learned from United States weather records about severe storms during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense

Observations: Extreme Weather

precipitation, tornadoes, hurricanes, and winter storm activity. They report several scientists have identified an increase in heavy precipitation, but “in other severe storm categories, the trends are downward.”

Kunkel (2003) reports a sizable increase in the frequency of extreme precipitation events in the United States since the 1920s and 1930s, but notes the frequencies of the late 1800s and early 1900s were about as high as those of the 1980s and 1990s, which suggests there may have been no century-long increase in this type of extreme weather.

Changnon (2003a) utilized a newly available extensive dataset on thunderstorm days covering the period 1896–1995 to assess long-term temporal variations in thunderstorm activity at 110 first-order weather reporting stations across the United States. By dividing the data into five 20-year segments, Changnon found “the 1936–1955 period was the nation’s peak of storm activity during the 100-year period ending in 1995.” During this central 20-year period, 40% of the 110 first-order weather stations experienced their greatest level of storm activity, whereas during the final 20-year period from 1976–1995, only 15% of the stations experienced their greatest level of storm activity.

In a separate paper, Changnon (2003b) investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States, finding mixed results. For example, he reports “one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms).” As mentioned earlier, however, had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon likely would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

Insurance losses, by contrast, rose rapidly over the past several decades, Changnon found, the primary reason being “a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society’s vulnerability.” When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events “do not exhibit an upward trend.” Thus, as Changnon emphasizes, “the adjusted loss values for these extremes [do] not indicate a shift due

to global warming.” He reiterates these real-world observations “do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO₂ levels, that call for weather extremes and storms to increase in frequency and intensity.”

Similar findings with respect to monetary loss trends due to extreme storm events were reported again by Changnon three years later in two separate papers.

In the first of these papers, working with data from the insurance industry, the researcher from the Illinois State Water Survey analyzed “catastrophes caused solely by high winds” that had had their losses adjusted so as to make them “comparable to current year [2006] values” (Changnon, 2009a). Although the average monetary loss of each year’s catastrophes “had an upward linear trend over time, statistically significant at the 2% level,” when the number of each year’s catastrophes was considered, “low values occurred in the early years (1952–1966) and in later years (1977–2006),” and “the peak of incidences came during 1977–1991.” Thus it was not surprising, as Changnon describes it, that “the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend.”

In his second paper from 2009, Changnon (2009b) utilized “records of extremely damaging storms in the United States during the years 1949–2006 ... to define their temporal distribution,” where such storms were defined as those producing losses greater than \$100 million, with a special subset defined as those producing losses greater than \$1 billion. At this extreme level of classification it was clearly evident “the number of storms at both loss levels has increased dramatically since 1990.” The author presents four possible explanations for his findings. First, he notes “storm measurement and data collection have improved over time.” Second and third, he says “the increases may also reflect natural variations in climate or a shift in climate due to global warming.” He then states “a fourth reason is that society has become more vulnerable to storm damages.”

References

- Balling Jr., R.C. and Cervený, R.S. 2003. Compilation and discussion of trends in severe storms in the United States: Popular perception vs. climate reality. *Natural Hazards* 29: 103–112.
- Changnon, S.A. 2003a. Geographical and temporal

variations in thunderstorms in the contiguous United States during the 20th century. *Physical Geography* **24**: 138–152.

Changnon, S.A. 2003b. Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming. *Natural Hazards* **29**: 273–290.

Changnon, S.A. 2009a. Temporal and spatial distributions of wind storm damages in the United States. *Climatic Change* **94**: 473–482.

Changnon, S.A. 2009b. Temporal changes in extremely damaging storms. *Physical Geography* **30**: 17–26.

Changnon, S.A. and Changnon, D. 2000. Long-term fluctuations in hail incidences in the United States. *Journal of Climate* **13**: 658–664.

Changnon, S.A. and Changnon, D. 2006. A spatial and temporal analysis of damaging snowstorms in the United States. *Natural Hazards* **37**: 373–389.

Gulev, S.K., Zolina, O., and Grigoriev, S. 2001. Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics* **17**: 795–809.

Hayden, B.P. 1999. Climate change and extratropical storminess in the United States: An assessment. *Journal of the American Water Resources Association* **35**: 1387–1397.

Kunkel, K.E. 2003. North American trends in extreme precipitation. *Natural Hazards* **29**: 291–305.

Lawson, B.D. 2003. Trends in blizzards at selected locations on the Canadian prairies. *Natural Hazards* **29**: 123–138.

National Research Council. 1999. *The Costs of Natural Disasters: A Framework for Assessment*. National Academy Press, Washington, DC, USA.

Schwartz, R.M. and Schmidlin, T.W. 2002. Climatology of blizzards in the conterminous United States, 1959–2000. *Journal of Climate* **15**: 1765–1772.

Trenberth, K.E. and Owen, T. 1999. Workshop on indices and indicators for climate extremes: Breakout group A: Storms. *Climatic Change* **42**: 9–21.

7.7.1.4 Other Regions

Sorrel *et al.* (2012) note the southern coast of the English Channel in northwestern France is “well suited to investigate long-term storminess variability because it is exposed to the rapidly changing North Atlantic climate system, which has a substantial influence on the Northern Hemisphere in general.”

They present “a reappraisal of high-energy estuarine and coastal sedimentary records,” finding “evidence for five distinct periods during the Holocene when storminess was enhanced during the past 6,500 years.”

The six scientists say “high storm activity occurred periodically with a frequency of about 1,500 years, closely related to cold and windy periods diagnosed earlier (Bond *et al.*, 2001; Wanner *et al.*, 2008; Wanner *et al.*, 2011).” They show “millennial-scale storm extremes in northern Europe are phase-locked with the period of internal ocean variability in the North Atlantic of about 1,500 years (Debret *et al.*, 2009),” with the last extreme stormy period “coinciding with the early to mid-Little Ice Age.” They note “in contrast, the warm Medieval Climate Optimum was characterized by low storm activity (Sorrel *et al.*, 2009; Sabatier *et al.*, 2012).” Sorrel *et al.* conclude, “in light of concerns about the impact of anthropogenic greenhouse gases on extreme storm events in the coming years/decades, our results indicate that modern coupled ocean-atmosphere dynamics at North Atlantic mid-latitudes should tend towards the low phase of the 1,500-year internal oceanic cycle, in contrast to Little Ice Age climate conditions,” which suggests warming should lead to relatively less storminess, contrary to what the models project.

Gulev *et al.* (2001) utilized sea-level pressure from NCEP/NCAR reanalysis data for the period 1958–1999 to develop a winter (January–March) climatology of cyclones (storms) for the Northern Hemisphere, from which they statistically analyzed only those cyclones that reached a sea-level pressure of 1000 mb or lower. They found the yearly mean number of winter cyclones for the period was 234, although there was pronounced interannual and spatial variability in the record. Linear trend estimates indicated a statistically significant (95% level) annual decline of 1.2 cyclones per year, suggesting there were 50 fewer cyclones in the Northern Hemisphere winter at the end of the record than there were 42 years prior (Figure 7.7.1.4.1). Additional data analyses suggest Northern Hemisphere winter cyclones are intensifying at quicker rates and are reaching greater maximum depths (lower sea-level pressure) at the end of the record than they were at the beginning of the record. However, the wintertime cyclones are also experiencing shorter life cycles, dissipating more quickly at the end of the record than at the beginning.

Winter storms in North America at the end of the

Observations: Extreme Weather

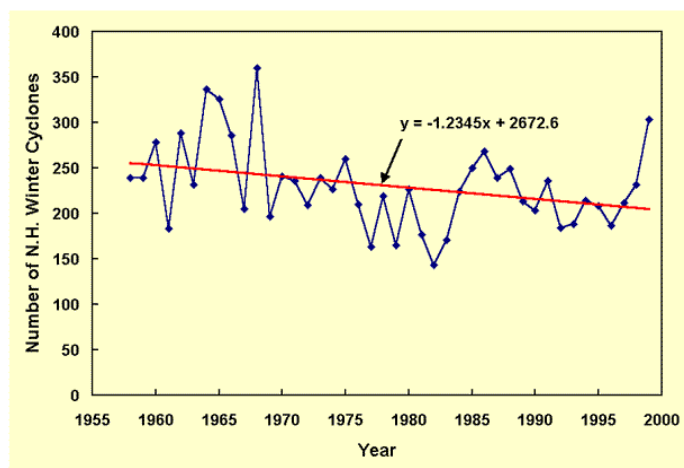


Figure 7.7.1.4.1. Yearly number of Northern Hemisphere cyclones over the period 1958–1999. Adapted from Gulev, S.K., Zolina, O., and Grigoriev, S. 2001. Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics* 17: 795–809.

twentieth century thus appear to have been maturing faster but dissipating more quickly than they were four decades earlier. Could this change be the result of global warming? The authors say the phenomenon is probably connected to large-scale features of atmospheric variability, such as the North Atlantic Oscillation and the North Pacific Oscillation. As for the large decrease reported in the annual number of Northern Hemisphere cyclones over the 42-year period, this observation is in direct opposition to model-based extreme weather predictions, which suggest the frequency of such events will increase as a result of global warming.

Simmonds and Keay (2000) employed a new cyclone finding and tracking scheme to conduct what they say “is arguably the most reliable analysis of Southern Hemisphere cyclone variability undertaken to date.” They found the annual average number of cyclones in the Southern Hemisphere steadily increased from the start of the assessment period. After peaking in 1972, however, there was an overall decline, and the authors state “the counts in the 1990s have been particularly low.” They detected a small increase in mean cyclone radius, but they note this effect has only “served to partially offset the effect of the remarkable decrease in cyclone numbers.” They also note the time series of Southern Hemisphere cyclone numbers shows an out-of-phase relationship with the Southern Hemisphere mean annual temperature record, which suggests, in their words, “that the downward trends in cyclone numbers are

associated with a warming Southern Hemisphere.”

Yu *et al.* (2004) point out, “according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones.” Because “understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events,” they devised a way to decipher the history of severe storms in the region of the southern South China Sea. At Youngshu Reef (9°32'–9°42'N, 112°52'–113°04'E), they used standard radiocarbon dating and TIMS U-series dating to determine the times of occurrence of storms strong enough to “relocate” large *Porites* coral blocks widespread on the reef flats there. Yu *et al.* determined “during the past 1000 years, at least six exceptionally strong storms occurred,” which they dated to approximately 1064 ± 30 , 1218 ± 5 , 1336 ± 9 , 1443 ± 9 , 1682 ± 7 , and 1872 ± 15 AD, yielding an average recurrence frequency of 160 years. Although models typically suggest that storms will become more frequent and severe in response to global warming and the warming of the twentieth century was the most significant of the past millennium, none of the six severe storms identified by Yu *et al.* occurred during the past millennium’s last century.

References

- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G. 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294: 2130–2136.
- Debret, M., Sebag, D., Costra, X., Massei, N., Petit, J.R., Chapron, E., and Bout-Roumazeilles, V. 2009. Evidence from wavelet analysis for a mid-Holocene transition in global climate forcing. *Quaternary Science Reviews* 28: 2675–2688.
- Gulev, S.K., Zolina, O., and Grigoriev, S. 2001. Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics* 17: 795–809.
- Sabatier, P., Dezileau, L., Colin, C., Briquet, L., Bouchette, F., Martinex, P., Siani, G., Raynal, O., and von Grafenstein, U. 2012. 7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events. *Quaternary Research* 77: 1–11.
- Simmonds, I. and Keay, K. 2000. Variability of Southern Hemisphere extratropical cyclone behavior, 1958–97. *Journal of Climate* 13: 550–561.

Sorrel, P., Debret, M., Billeaud, I., Jaccard, S.L., McManus, J.F., and Tessier, B. 2012. Persistent non-solar forcing of Holocene storm dynamics in coastal sedimentary archives. *Nature Geoscience* 5: 892–896.

Sorrel, P., Tessier, B., Demory, F., Delsinne, N., and Mouaze, D. 2009. Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France). *Quaternary Science Reviews* 28: 499–516.

Walsh, K.J.E. and Ryan, B.F. 2000. Tropical cyclone intensity increase near Australia as a result of climate change. *Journal of Climate* 13: 3029–3036.

Wanner, H., Beer, J., Butikofer, J., Crowley, T.J., Cubasch, U., Fluckiger, J., Goose, H., Grosjean, M., Fortunat, J., Kaplan, J.O., Kuttel, M., Muller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., and Widmann, M. 2008. Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* 27: 1791–1828.

Wanner, H., Solomina, O., Grosjean, M., Ritz, S., and Jetel, M. 2011. Structure and origin of Holocene cold events. *Quaternary Science Reviews* 30: 3109–3123.

Yu, K.-F., Zhao, J.-X., Collerson, K.D., Shi, Q., Chen, T.-G., Wang, P.-X., and Liu, T.-S. 2004. Storm cycles in the last millennium recorded in Yongshu Reef, southern South China Sea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 210: 89–100.

7.7.1.5 Global

Although most studies focus on storms trends for a given location or region, some researchers have attempted to examine the trends for the globe as a whole. This section reviews that research.

Huntington (2006) states there is “a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al.*, 1991; Loaciga *et al.*, 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al.*, 2001).” He reiterates the long-held climate-model-derived notion that “an intensification of the water cycle may lead to changes in water-resource availability,” meaning “floods and droughts,” as well as “an increase in the frequency and intensity of tropical storms.” He proceeds to explore these theoretical expectations via a review of the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and other parameters.

“On a globally averaged basis,” according to Huntington, “precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998).” He also notes “an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987),” and a recent reanalysis of these trends for the period 1920–1995 “confirmed an increase in world continental runoff during the 20th century (Labat *et al.*, 2004).”

These findings suggest global warming may indeed have intensified the global hydrologic cycle over the twentieth century. However, Huntington also reports “the empirical evidence to date does not consistently support an increase in the frequency or intensity of tropical storms and floods.” As for droughts, he says the “evidence indicates that summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al.*, 2000).”

Thus there appears to have been a slight intensification of the hydrologic cycle throughout the twentieth century over Earth’s land area, which may or may not have been caused by the concomitant warming of the globe, but it also appears there was no intensification of deleterious weather phenomena such as tropical storms, floods, and droughts. In addition, Smith *et al.* (2006) demonstrate over the period 1979–2004, when the IPCC claims the planet experienced a warming unprecedented over the past one to two millennia, there was no net change in global precipitation (over both land and water).

Gulev and Grigorieva (2004) analyzed ocean wave heights (a proxy for storms) using the Voluntary Observing Ship wave data of Worley *et al.* (2005) to characterize significant wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists report “the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950,” which would seem to vindicate model projections of increasing storms. “However,” they continue, “for the period 1885–2002 there is no secular trend in HS in the Atlantic” and “the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002.”

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century “is comparable with that for recent decades,” and “in the Atlantic it is even higher than during the last 5

decades.” In the Atlantic the mean HS of the decade of the 1920s is higher than that of any recent decade, and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific it also appears the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes a definitive answer on this point. Nevertheless, it is clear that annual mean wave height (a proxy for storminess) over the last decade of the twentieth century was not higher than annual wave height values earlier in the century.

Key and Chan (1999) analyzed trends in seasonal and annual frequencies of low-pressure centers (cyclones) at 1000-mb (near-surface) and 500-mb heights for six latitude regions (0–30°N, 0–30°S, 30–60°N, 30–60°S, 60–90°N and 60–90°S) over the four-decade period 1958–1997, while also determining trends in cyclone frequencies for El Niño vs. La Niña years. They found both positive and negative trends (some significant and some not) in cyclone frequency at both atmospheric levels over the 40-year period. Cyclone frequencies at both atmospheric levels were also found to be lower at all latitude regions except two (30–60°S and 60–90°S) during El Niño years, as opposed to La Niña years. Although Key and Chan found some regional differences in cyclone frequencies, there was no indication of any global trend, positive or negative. They also found fewer cyclones occur during warmer El Niño years than during cooler La Niña years, appearing to further invalidate model-based claims that global warming will result in more storms globally..

References

Arnell, N.W., Liu, C., Compagnucci, R., da Cunha, L., Hanaki, K., Howe, C., Mailu, G., Shiklomanov, I., and Stakhiv, E. 2001. Hydrology and water resources. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. (Eds.) *Climate Change 2001: Impacts, Adaptation and Vulnerability, The Third Assessment Report of Working Group II of the Intergovernmental Panel on Climate Change*, Cambridge, University Press, Cambridge, UK, pp. 133–191.

Dai, A., Fung, I.Y., and DelGenio, A.D. 1997. Surface observed global land precipitation variations during 1900–1998. *Journal of Climate* **10**: 2943–2962.

DelGenio, A.D., Laxis, A.A., and Ruedy, R.A. 1991. Simulations of the effect of a warmer climate on atmospheric humidity. *Nature* **351**: 382–385.

Gulev, S.K. and Grigorieva, V. 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research Letters* **31**: 10.1029/2004GL021040.

Held, I.M. and Soden, B.J. 2000. Water vapor feedback and global warming. *Annual Review of Energy and Environment* **25**: 441–475.

Hulme, M., Osborn, T.J., and Johns, T.C. 1998. Precipitation sensitivity to global warming: comparisons of observations with HadCM2 simulations. *Geophysical Research Letters* **25**: 3379–3382.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* **319**: 83–95.

Key, J.R. and Chan, A.C.K. 1999. Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophysical Research Letters* **26**: 2053–2056.

Labat, D., Godderis, Y., Probst, J.L., and Guyot, J.L. 2004. Evidence for global runoff increase related to climate warming. *Advances in Water Resources* **27**: 631–642.

Loaciga, H.A., Valdes, J.B., Vogel, R., Garvey, J., and Schwarz, H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology* **174**: 83–127.

Probst, J.L. and Tardy, Y. 1987. Long range streamflow and world continental runoff fluctuations since the beginning of this century. *Journal of Hydrology* **94**: 289–311.

Robock, A., Konstantin, Y.V., Srinivasan, J.K., Entin, J.K., Hollinger, N.A., Speranskaya, N.A., Liu, S., and Nampkai, A. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* **81**: 1281–1299.

Smith, T.M., Yin, X., and Gruber, A. 2006. Variations in annual global precipitation (1979–2004), based on the Global Precipitation Climatology Project 2.5° analysis. *Geophysical Research Letters* **33**: 10.1029/2005GL025393.

Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* **42**: 327–339.

Worley, S.J., Woodruff, S.D., Reynolds, R.W., Lubker, S.J., and Lott, N. 2005. ICOADS release 2.1 data and products. *International Journal of Climatology* **25**: 823–842.

7.7.2 Dust Storms

Will dust storms increase in response to CO₂-induced global warming? That question requires an answer given model-based projections that both the

frequency and intensity of extreme weather events will increase in the future.

According to Griffin *et al.* (2002), “as much as two billion metric tons of dust are lifted into the Earth’s atmosphere every year,” and soil particulates from Africa and Asia cross both the Atlantic and Pacific Oceans. As a result of the trans-Pacific transport, Wilkening *et al.* (2000) state “the once-pristine air above the North Pacific Ocean is polluted,” and they go on to list several implications for a number of terrestrial and oceanic ecosystems. They also note we can expect these impacts to increase with economic expansion around the world, and by analogy we can infer such impacts have likely grown in tandem with population and industrialization over the past century or so. Griffin *et al.* remark dust storms originating in North Africa “routinely affect the air quality in Europe and the Middle East,” and millions of tons of African sediment “fall on the North Amazon Basin of South America every year.”

Prospero (2001) suggests nearly everyone in the United States living east of the Mississippi River is affected by dust of African origin. Likewise, Prospero and Lamb (2003) report measurements made from 1965 to 1998 in the Barbados trade winds show large interannual changes in the concentration of dust of African origin that are highly anticorrelated with the prior year’s rainfall in the Soudano-Sahel, and they note the IPCC report of Houghton *et al.* (2001) “assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts.” They say “there is little firm evidence to support either of these assumptions.”

Griffin *et al.* report in April 2001 a large dust cloud originating over the Gobi Desert of China “moved eastward across the globe, crossing Korea, Japan, the Pacific (in five days), North America (causing sporadic reports of poor air quality in the United States), the Atlantic Ocean and then Europe.”

Grousset *et al.* (2003) studied dust samples collected in the French Alps, analyzing their mineralogical and geochemical composition, including the isotopic composition of the neodymium contained in the minerals. They then reconstructed air mass backward trajectories from archived meteorological data, including corroboration by satellite imagery, and used a global transport model driven by assimilated meteorology to simulate dust deflation and long-range transport. Their work revealed one of the sets of dust samples came from

North Africa, and the second set originated in the Takla-Makan desert of China. Their work additionally suggested the latter set of dust particles had traveled “more than 20,000 km in about two weeks, and along their journey, crossed China, the North Pacific, North America and then the North Atlantic Ocean.” That knowledge, they write, “is important from the viewpoint of understanding the dust itself” as well as “the heavy metal, fungal, bacterial and viral pollution that may be associated with it.”

Liu *et al.* (2004) analyzed trends in spring dust storm frequency for western and southwestern China-Mongolia for the period 1952–2003, finding both interannual and interdecadal trends throughout the 52-year period. By decade, the number of spring dust storms varied from 21 in the 1950s, to 44 in the 1960s, to a high of 60 in the 1970s, then back down to 35 in the 1980s, and a low of 25 in the 1990s. In addition, they determined strong and cold Siberian air masses enhance dust storm numbers, whereas weaker and warmer Siberian air masses lower them. Thus, if warming of the globe increases temperatures in the northern part of China and Mongolia, Liu *et al.* say “the China-Mongolia ridge will continue to rise and suppress Mongolian cyclones and dust storm activities in Western China-Mongolia.”

Zhu *et al.* (2008) note “changes in occurrences of natural disasters, which are possibly associated with global warming, have been receiving ever-increasing attention world wide,” and the “dust storm is one of the severe disastrous weather [phenomena] in China.” In this regard, however, and in contrast to the general tenor of most model-based discussions of global warming and extreme weather, they write, “a number of studies have shown that the spring dust storm frequency (DSF) bears a negative correlation with the local surface air temperature, and exhibits a downward trend over the past 50 years,” citing the studies of Qian *et al.* (2002), Zhou and Zhang (2003), Zhai and Li (2003), Zhao *et al.* (2004), Fan *et al.* (2006), and Gong *et al.* (2006, 2007).

Zhu *et al.* explored “the long-term variation of Chinese DSF in spring (March to May), and its possible linkage with the global warming and its related circulation changes in the Northern Hemisphere,” using data from 258 stations within the region surrounding Lake Baikal (70–130°E, 45–65°N) over the period 1954 to 2007. The authors found a “prominent warming” in recent decades, as well as “an anomalous dipole circulation pattern” in the troposphere that “consists of a warm anti-cyclone centered at 55°N and a cold cyclone centered around

30°N,” leading to “a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian regions, which suppress the frequency of occurrence and the intensity of the Mongolian cyclones and result in the decreasing DSF in North China.” Rising temperatures, therefore, served as the trigger mechanisms in trends in DSF, but not in the general manner projected by the IPCC: Rising temperatures reduced DSF instead of increasing it.

Lim *et al.* (2005) examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, from which they produced a proxy record of major Asian dust events that reached the region over the past 6,500 years. This analysis indicated the EQC was relatively low 6,500–4,000 years BP, high 4,000–2,000 years BP, and low again from 2,000 years BP to the present, with the most recent 1,500 years BP being lower in EQC than any previous time in the record. The Asian dust time series also was found to contain significant millennial- and centennial-scale periodicities. Cross-spectral analysis between the EQC and proxy solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the three researchers to conclude the centennial-scale periodicities in the EQC can be ascribed primarily to short-term fluctuations in solar activity.

Engelstaedter *et al.* (2003) used dust storm frequency (DSF) data from 2,405 stations represented in the International Station Meteorological Climate Summary as a surrogate measure of dust emissions to test the assumption that vegetation is an important control of dust emission at the global scale. To represent vegetation cover, they used two independent datasets: a satellite-derived distribution of actual vegetation types, and a model-derived distribution of potential natural vegetation. Employing these tools, they learned “the highest DSFs are found in areas mapped by DeFries and Townshend (1994) as bare ground,” and “moderate DSFs occur in regions with more vegetation, i.e., shrubs & bare ground, and lowest DSFs occur in grasslands, forests, and tundra,” where ground cover is highest. Thus they conclude “average DSF is inversely correlated with leaf area index (an index of vegetation density) and net primary productivity,” suggesting whatever increases vegetative cover should reduce the severity of dust emissions from the soil beneath as well as the dust’s subsequent transport to various parts of the world.

Evan *et al.* (2006) reached a similar conclusion,

applying a new daytime over-water dust detection algorithm for the Advanced Very High Resolution Radiometer (AVHRR) to 24 years (1982–2005) of wintertime satellite imagery over West Africa and the surrounding Atlantic Ocean and comparing it with a similarly derived Normalized Difference Vegetation Index (NDVI) shown to be responsive to vegetation variability in the Sahel. A strong relationship was found to exist between tropical North Atlantic dustiness and the vegetation index, “suggesting the possibility that vegetation changes in the Sahel play an important role in variability of downwind dustiness.” Evan *et al.* conclude “dust mobilization may be mediated by vegetation through increases in soil stability and reductions of wind stress on the surface, when more vegetation is present,” which “would be consistent with the modeling studies of Gillette (1999) and Engelstaedter *et al.* (2003).”

Rising atmospheric CO₂ might play a valuable role in this regard. The well-documented increase in plant water use efficiency that results from increases in the air’s CO₂ content should allow more plants to grow in the arid source regions of Earth’s dust clouds, helping stabilize and shield the soil, decreasing its susceptibility to wind erosion and reducing the amounts of dust made airborne and transported by globe-girdling winds. Moreover, the propensity for elevated CO₂ concentrations to increase soil moisture content as a consequence of CO₂-induced reductions in plant transpiration should also encourage plant growth. And the ability of extra atmospheric CO₂ to enhance the growth of cryptobiotic soil crusts should directly stabilize the surface of the soil, even in the absence of higher plants. Direct support for the role of elevated CO₂ in increasing desert biomass is provided by the recent work of Donohue *et al.* (2013), who found foliage has increased over warm, dry regions by 5 to 10% from 1982 to 2010.

We conclude with a review of the findings of Piao *et al.* (2005), who used a “time series data set of Normalized Difference Vegetation Index (NDVI) obtained from the Advanced Very High Resolution Radiometer available from 1982 to 1999 (Tucker *et al.*, 2001; Zhou *et al.*, 2001), and precipitation and temperature data sets, to investigate variations of desert area in China by identifying the climatic boundaries of arid area and semiarid area, and changes in NDVI in these areas.” They found “average rainy season NDVI in arid and semiarid regions both increased significantly during the period 1982–1999.” The NDVI increased for 72.3% of total arid regions and for 88.2% of total semiarid regions,

such that the area of arid regions decreased by 6.9% and the area of semiarid regions decreased by 7.9%. They also report that by analyzing Thematic Mapper satellite images, “Zhang *et al.* (2003) documented that the process of desertification in the Yulin area, Shannxi Province showed a decreased trend between 1987 and 1999,” and “according to the national monitoring data on desertification in western China (Shi, 2003), the annual desertification rate decreased from 1.2% in the 1950s to -0.2% at present.”

Noting “variations in the vegetation coverage of these regions partly affect the frequency of sand-dust storm occurrence (Zou and Zhai, 2004),” Piao *et al.* conclude “increased vegetation coverage in these areas will likely fix soil, enhance its anti-wind-erosion ability, reduce the possibility of released dust, and consequently cause a mitigation of sand-dust storms.” And, as pointed out in previous studies, they report “recent studies have suggested that the frequencies of strong and extremely strong sand-dust storms in northern China have significantly declined from the early 1980s to the end of the 1990s (Qian *et al.*, 2002; Zhao *et al.*, 2004).”

References

- DeFries, R.S. and Townshend, J.R.G. 1994. NDVI-derived land cover classification at a global scale. *International Journal of Remote Sensing* **15**: 3567–3586.
- Donohue, R.J., Roderick, M.L., McVicar, T.R., and Farquhar, G.D. 2013. CO₂ fertilization has increased maximum foliage cover across the globe’s warm, arid environments. *Geophysical Research Letters* **40**: 3031–3035.
- Engelstaedter, S., Kohfeld, K.E., Tegen, I., and Harrison, S.P. 2003. Controls of dust emissions by vegetation and topographic depressions: An evaluation using dust storm frequency data. *Geophysical Research Letters* **30**: 10.1029/2002GL016471.
- Evan, A.T., Heidinger, A.K., and Knippertz, P. 2006. Analysis of winter dust activity off the coast of West Africa using a new 24-year over-water advanced very high resolution radiometer satellite dust climatology. *Journal of Geophysical Research* **111**: 10.1029/2005JD006336.
- Fan, Y.-D., Shi, P.-J., Zhu, A.-J., Gong, M.-X., and Guan, Y. 2006. Analysis of connection between dust storm and climate factors in northern China. *Journal of Natural Disasters* **15**: 12–18.
- Gillette, D. 1999. A qualitative geophysical explanation for “hot spot” dust emitting source regions. *Contributions to Atmospheric Physics* **72**: 67–77.
- Gong, D.-Y., Mao, R., and Fan, Y.-D. 2006. East Asian dust storm and weather disturbance: Possible links to the Arctic Oscillation. *International Journal of Climatology* **26**: 1379–1396.
- Gong, D.-Y., Mao, R., Shi, P.-J., and Fan, Y.-D. 2007. Correlation between east Asian dust storm frequency and PNA. *Geophysical Research Letters* **34**: 10.1029/2007GL029944.
- Griffin, D.W., Kellogg, C.A., Garrison, V.H., and Shinn, E.A. 2002. The global transport of dust. *American Scientist* **90**: 228–235.
- Grousset, F.E., Ginoux, P., Bory, A., and Biscaye, P.E. 2003. Case study of a Chinese dust plume reaching the French Alps. *Geophysical Research Letters* **30**: 10.1029/2002GL016833.
- Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Xiaosu, D., Maskell, K., and Johnson, C.A. (Eds.) 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, UK. (Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change.)
- Lim, J., Matsumoto, E., and Kitagawa, H. 2005. Eolian quartz flux variations in Cheju Island, Korea, during the last 6500 yr and a possible Sun-monsoon linkage. *Quaternary Research* **64**: 12–20.
- Liu, C.-M., Qian, Z.-A., Wu, M.-C., Song, M.-H., and Liu, J.-T. 2004. A composite study of the synoptic differences between major and minor dust storm springs over the China-Mongolia areas. *Terrestrial, Atmospheric and Oceanic Sciences* **15**: 999–1018.
- Piao, S., Fang, J., Liu, H., and Zhu, B. 2005. NDVI-indicated decline in desertification in China in the past two decades. *Geophysical Research Letters* **32**: 10.1029/2004GL021764.
- Prospero, J.M. 2001. African dust in America. *Geotimes* **46**(11): 24–27.
- Prospero, J.M. and Lamb, P.J. 2003. African droughts and dust transport to the Caribbean: climate change implications. *Science* **302**: 1024–1027.
- Qian, W.-H., Quan, L.-S., and Shi, S.-Y. 2002. Variations of the dust storm in China and its climatic control. *Journal of Climate* **15**: 1216–1229.
- Qian, Z.A., Song, M.H., and Li, W.Y. 2002. Analysis on distributive variation and forecast of sand-dust storms in recent 50 years in north China. *Journal of Desert Research* **22**: 106–111.
- Shi, Y.F. (Ed.) 2003. *An Assessment of the Issues of Climatic Shift from Warm-Dry to Warm-Wet in Northwest China*. China Meteorology, Beijing.

Observations: Extreme Weather

Tucker, C.J., Slayback, D.A., Pinzon, J.E., Los, S.O., Myneni, R.B., and Taylor, M.G. 2001. Higher northern latitude NDVI and growing season trends from 1982 to 1999. *International Journal of Biometeorology* **45**: 184–190.

Wilkening, K.E., Barrie, L.A., and Engle, M. 2000. Trans-Pacific air pollution. *Science* **290**: 65–67.

Zhai, P.M. and Li, X.Y. 2003. On climate background of dust storms over northern China. *Chinese Journal of Geophysics* **58**: 125–131.

Zhang, L., Yue, L.P., and Xia, B. 2003. The study of land desertification in transitional zones between the MU US desert and the Loess Plateau using RS and GIS—A case study of the Yulin region. *Environmental Geology* **44**: 530–534.

Zhao, C., Dabu, X., and Li, Y. 2004. Relationship between climatic factors and dust storm frequency in Inner Mongolia of China. *Geophysical Research Letters* **31**: 10.1029/2003GL018351.

Zhou, L.M., Tucker, C.J., Kaufmann, R.K., Slayback, D.A., Shabanov, N.V., and Myneni, R.B. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research* **106**: 20,069–20,083.

Zhou, Z.-J. and Zhang, G.-C. 2003. Typical severe dust storms in northern China: 1954–2002. *Chinese Science Bulletin* **48**: 1224–1228.

Zhu, C., Wang, B., and Qian, W. 2008. Why do dust storms decrease in northern China concurrently with the recent global warming? *Geophysical Research Letters* **35**: 10.1029/2008GL034886.

Zou, X.K. and Zhai P.M. 2004. Relationship between vegetation coverage and spring dust storms over northern China. *Journal of Geophysical Research* **109**: 10.1029/2003JD003913.

7.7.3 Hail

Insurance costs related to life and property damage caused by extreme weather events have been steadily rising in the United States and elsewhere, and it is not uncommon for many in the insurance industry and government to place the blame for this development on what they claim are significant increases in the frequencies and intensities of severe weather events, since climate models suggest these phenomena should be increasing as a consequence of CO₂-induced global warming. But is this explanation correct?

According to the latest IPCC report, there is “insufficient evidence” to determine whether such

small-scale severe weather events as hail are changing in response to what they perceive to be the unprecedented modern rise in both atmospheric CO₂ and temperature (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The following research, however, strongly suggests changes in atmospheric CO₂ and temperature have exerted no measurable influence on hail trends, when hail data are properly analyzed.

After describing and analyzing property losses caused by a series of Midwestern U.S. hailstorms that occurred on 13–14 April 2006, totaling \$1.822 billion, “an amount considerably more than the previous record high of \$1.5 billion set by an April 2001 hail event,” Changnon (2009) described and analyzed the “top ten” hail-loss events that occurred in the United States over the period 1950–2006, finding “an increase over time in [hail event] frequency and losses with most major events occurring since 1990.”

These findings would appear to support the contention that global warming is causing more hail events. However, the Illinois State Water Survey researcher opines only “two factors could have affected this increase.” One of them, in his words, could have been “more frequent occurrences of major cases of strong atmospheric instability, leading to the development of supercell thunderstorms capable of persisting for many hours, covering large areas, and producing large hailstones.” He says this scenario “has not been measured and cannot be verified.” The second factor, as he describes it, “is the expansion of the nation’s metropolitan areas, enhancing the target for hail damages to property,” in support of which he notes “urban population in the U.S. since 1960 increased by 56% and urban areas grew by 154%,” according to the World Almanac (2008), making a good case for the second of the two factors Changnon suggests.

This latter explanation also was favored by Changnon in an earlier study (Changnon, 2003) in which he investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century. He found trends in various weather extremes over this period were mixed, noting, “one trend is upwards (heavy rains-floods), others are downward [including “hail, hurricanes, tornadoes, and severe thunderstorms”], and others are unchanging flat trends (winter storms and wind storms).” As for why U.S. insurance losses due to most extreme weather events rose so rapidly throughout the past several decades, Changnon

reports “the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society’s vulnerability.”

Further support for this thesis comes from the even earlier work of Kunkel *et al.* (1999), who analyzed historical trends in several different types of extreme weather events, together with their societal impacts, near the close of the last century. They found most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses. However, they found “trends in most related weather and climate extremes do not show comparable increases with time.” These observations led them to conclude the increasing economic losses “are primarily due to increasing vulnerability arising from a variety of societal changes,” and in this regard they found “increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors.”

When the temporal span of analysis is expanded even further, the claim that global warming is increasing hail events is completely debunked. Changnon and Changnon (2000), for example, analyzed hail-day and thunder-day occurrences over the century-long period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the United States. This effort revealed thunder-day frequency peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence fell to only 65% of what it had been at mid-century, dropping so low there was a decline in national hail insurance losses over the final two decades of the study.

Locations beyond the United States yield similar results. Bielec (2001) analyzed thunderstorm data obtained at Cracow, Poland, described as possessing “one of the few continuous records in Europe with an intact single place of observation and duration of over 100 years.” Over the length of this record, there were 2,470 days with thunderstorms, an average of about 25 days per year. The highest annual number of thunderstorm days was 37, recorded in 1968 and again in 1975, and the lowest annual number was 9, in 1904. Close analysis of the data revealed a slight but non-significant linear increase of 1.6 storms per year from the beginning to the end of the record.

From 1930 onward, however, the trend is negative, revealing a linear decrease of 1.1 storms per year. With respect to the annual number of thunderstorms with hail, Bielec reports there was a decrease over the hundred-year period.

From a historical hail dataset of 753 stations compiled by the National Meteorological Information Center of China, which “includes hail data for all weather stations in the surface meteorological observational network over the whole of China from 1951 to 2005,” Xie *et al.* (2008) “chose 523 stations with complete observations from 1960 to 2005” to study “annual variations and trend[s] of hail frequency across mainland China during 1960–2005.”

As is evident in Figure 7.7.3.1, Xie *et al.* found “no trend in the mean Annual Hail Days (AHD) from 1960 to [the] early 1980s but a significant decreasing trend afterwards.” This downturn was concomitant with a warming of the globe the IPCC claims was unprecedented over the past one to two millennia, leading the three authors to conclude global warming may actually imply “a possible reduction of hail occurrence.”

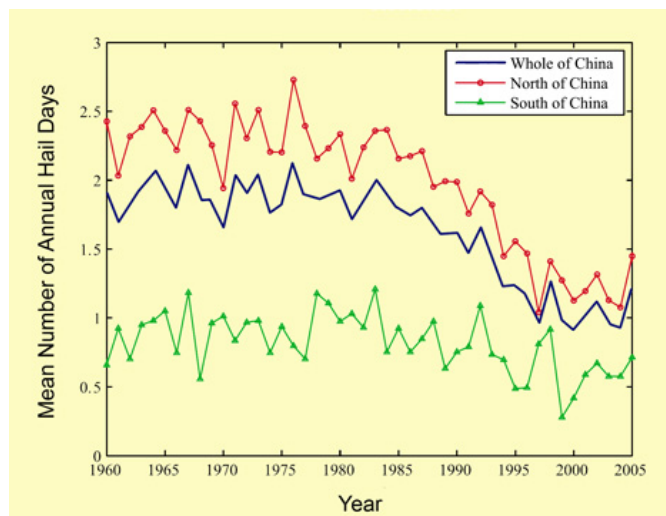


Figure 7.7.3.1. Mean Annual Hail Day variations and trends in northern China, southern China, and the whole of China. Adapted from Xie, B., Zhang, Q., and Wang, Y. 2008. Trends in hail in China during 1960–2005. *Geophysical Research Letters* 35: 10.1029/2008GL034067.

Recognizing Xie *et al.* (2008) found a “significant decreasing trend of hail frequency in most of China from the early 1980s based on 46 years of data during 1960–2005,” Xie and Zhang (2010) set out to learn whether there also had been any change in another type of extremeness (hailstone size), noting “changes

in hail size are also an important aspect of hail climatology.” They examined the long-term trend of hail size in four regions of China over the period 1980–2005, using maximum hail diameter data obtained from the Meteorological Administrations of Xinjiang Uygur Autonomous Region (XUAR), Inner Mongolia Autonomous Region (IMAR), Guizhou Province, and Hebei Province.

The researchers found an uptrend in maximum hail diameter in Hebei, a flat trend in XUAR, and a slight downtrend in both Guizhou and IMAR, but “none of the trends is statistically significant.”

These results, combined with the other findings presented above, demonstrate global warming, CO₂-induced or otherwise, likely has had nothing to do with the increasing damages caused by extreme weather events in general. It also has had no tendency to increase the occurrence of hail storms, at least in the United States, China, and portions of Poland for which pertinent data have been properly analyzed.

References

- Bielec, Z. 2001. Long-term variability of thunderstorms and thunderstorm precipitation occurrence in Cracow, Poland, in the period 1896–1995. *Atmospheric Research* **56**: 161–170.
- Changnon, S.A. 2003. Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming. *Natural Hazards* **29**: 273–290.
- Changnon, S.A. 2009. Increasing major hail losses in the U.S. *Climatic Change* **96**: 161–166.
- Changnon, S.A. and Changnon, D. 2000. Long-term fluctuations in hail incidences in the United States. *Journal of Climate* **13**: 658–664.
- Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098.
- World Almanac. 2008. *The World Almanac and Book of Facts*. U.S. Cities, States and Population. World Almanac, New York, New York, USA.
- Xie, B. and Zhang, Q. 2010. Observed characteristics of hail size in four regions in China during 1980–2005. *Journal of Climate* **23**: 4973–4982.
- Xie, B., Zhang, Q., and Wang, Y. 2008. Trends in hail in China during 1960–2005. *Geophysical Research Letters* **35**: 10.1029/2008GL034067.

7.7.4 Tornadoes

According to the latest IPCC report, there is “insufficient evidence” to determine whether small-scale severe weather events such as tornadoes are changing in response to what the IPCC perceives to be an unprecedented rise in both atmospheric CO₂ and temperature of the modern era (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The research reviewed below, however, strongly suggests changes in CO₂ and temperature have exerted no measurable influence on tornado trends. Because tornadoes often occur in conjunction with other severe storm events, other features of severe storms are frequently mentioned in the studies discussed below.

In a review of “temporal fluctuations in weather and climate extremes that cause economic and human health impacts,” Kunkel *et al.* (1999) analyzed empirical data related to historical trends of several different types of extreme weather events and their societal impacts. This work revealed “most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses.” However, they found “trends in most related weather and climate extremes do not show comparable increases with time,” suggesting “increasing losses are primarily due to increasing vulnerability arising from a variety of societal changes, including a growing population in higher risk coastal areas and large cities, more property subject to damage, and lifestyle and demographic changes subjecting lives and property to greater exposure.” Regarding tornado losses, they specifically state “increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors.”

Balling and Cervený (2003) also reviewed the scientific literature to determine what had been learned about severe storms in the United States during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense precipitation, tornadoes, hurricanes, and winter storm activity. They found several scientists had identified an increase in heavy precipitation, but “in other severe storm categories, the trends are downward,” just the opposite of what climate models contend should be the case.

Noting “media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe

weather events,” with these changes implied as being mostly for the worse, Hage (2003) used “previously unexploited written resources such as daily and weekly newspapers and community histories” to establish a database adequate for determining long-term trends of destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) in the prairie provinces of Alberta and Saskatchewan in western Canada over the period 1882 to 2001. Because “sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns,” Hage writes, “extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors.” The results of these operations are stated quite simply: “All intense storms showed no discernible changes in frequency after 1940.

Changnon (2003) investigated trends in both severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States. He found trends in various weather extremes were mixed, noting “one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms).” Had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

As to why insurance losses rose so rapidly over the past several decades, Changnon reports “the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society’s vulnerability.” When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events “do not exhibit an upward trend.” Changnon emphasizes, “the adjusted loss values for these extremes [do] not indicate a shift due to global warming.” These real-world observations, he notes, “do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO₂ levels, that call for weather extremes and storms to increase in frequency and intensity.”

Khandekar (2003) briefly reviews what he learned about extreme weather events in Canada while conducting a study of the subject for the government of Alberta. He notes his research led him to conclude “extreme weather events such as heat waves, rain storms, tornadoes, winter blizzards, etc., [were] not increasing anywhere in Canada at [that] time.” In addition, he notes a special issue of *Natural Hazards* (Vol. 29, No. 2) concluded much the same thing about other parts of the world, citing a survey article by Robert Balling, who found “no significant increase in overall severe storm activity (hurricanes, thunderstorms/tornadoes, winter blizzards) across the conterminous United States,” and the previously cited work of Changnon.

Daoust (2003) catalogued daily tornado frequencies for each county of Missouri (USA) for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state’s 115 counties, its six climatic divisions, and the entire state. This work revealed the presence of positive trends in tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant but negative. At the level of the entire state, Daoust reported “for the last 53 years, no long-term trend in tornado days can be found.”

Diffenbaugh *et al.* (2008) briefly reviewed what is known about responses of U.S. tornadoes to rising temperatures. On the theoretical side of the issue, they indicate there are competing ideas with regard to whether tornadoes might become more or less frequent and/or severe as the planet warms. On the observational side, there is also much uncertainty about the matter. They write, for example, “the number of tornadoes reported in the United States per year has been increasing steadily (~14 per year) over the past half century,” but they note “determining whether this is a robust trend in tornado occurrence is difficult” because “the historical record is both relatively short and non-uniform in space and time.” In addition, the increase in yearly tornado numbers runs parallel with the concurrent increase in the country’s population, which makes for better geographical coverage and more complete (i.e., numerous) observations.

On the other hand, the three researchers report the number of tornadoes classified as the most damaging (F2–F5 on the Fujita scale) may have truly decreased over the past five decades (1954–2003), as their frequency of occurrence actually runs counter to the

trend of the nation's population. The graphs they present show yearly F2–F5 tornado numbers in the latter half of the record period dropping to only about half of what they were during the first half of the record, while corresponding data from the U.S. Southern Great Plains show damaging tornado numbers dropping to only about a third of what they were initially. Nevertheless, Diffenbaugh *et al.* consider the question posed in the title of their paper—Does global warming influence tornado activity?—to be unresolved, stating “determining the actual background occurrence and trend in tornado activity over recent decades will certainly require further development of other analysis approaches.”

References

- Balling Jr., R.C. and Cervený, R.S. 2003. Compilation and discussion of trends in severe storms in the United States: Popular perception vs. climate reality. *Natural Hazards* **29**: 103–112.
- Changnon, S.A. 2003. Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming. *Natural Hazards* **29**: 273–290.
- Daoust, M. 2003. An analysis of tornado days in Missouri for the period 1950–2002. *Physical Geography* **24**: 467–487.
- Diffenbaugh, N.S., Trapp, R.J., and Brooks, H. 2008. Does global warming influence tornado activity? *EOS, Transactions, American Geophysical Union* **89**: 553–554.
- Hage, K. 2003. On destructive Canadian prairie windstorms and severe winters. *Natural Hazards* **29**: 207–228.
- Khandekar, L. 2003. Comment on WMO statement on extreme weather events. *EOS, Transactions, American Geophysical Union* **84**: 428.
- Kunkel, K.E. 2003. North American trends in extreme precipitation. *Natural Hazards* **29**: 291–305.
- Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098.
- McPhaden and Zhang (2002), for example, studied surface winds over the Pacific Ocean and the currents they produce in the water below that flow outward from the equator and eventually sink and flow back from both hemispheres to meet and rise near the equator. They discovered over the period 1950–1999, this overturning circulation of the ocean “has been slowing down since the 1970s, causing a decrease in upwelling of about 25% in an equatorial strip between 9°N and 9°S.” The scientists say the gradual decline may have been caused by global warming—the opposite of what climate models suggest should happen—but they also note natural variability may just as easily have been the cause of what they observed.
- Siegismund and Schrum (2001) investigated wind speed characteristics over the North Sea for the period 1958–1997. They found “the annual mean wind speed for the North Sea shows a rising trend of ~10% during the last 40 years,” in harmony with what climate models typically predict. In addition, they determined “since the early 1970s ‘strong wind’ events are more frequent than in the 1960s,” also in harmony with model-based predictions. As for the cause of these phenomena, however, the researchers say their data “may suggest an anthropogenic origin, but this hypothesis can neither be supported nor disproved by analyzing such short time series.”
- Slonosky *et al.* (2000) analyzed atmospheric surface pressure data from 51 stations located throughout Europe and the eastern North Atlantic over the period 1774–1995, finding atmospheric circulation over Europe was “considerably more variable, with more extreme values in the late 18th and early 19th centuries than in the 20th century.” Pirazzoli (2000) studied tide-gauge and meteorological (wind and atmospheric pressure) data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions (storms) and strong surge winds for this region “are becoming less frequent.”
- Barring and von Storch (2004) analyzed pressure readings for Lund (since 1780) and Stockholm (since 1823) in Sweden to create a record of storminess. They found their proxy time series for storminess were “remarkably stationary in their mean, with little variations on time scales of more than one or two decades.” Specifically, they report “the 1860s–70s was a period when the storminess indices showed general higher values,” as was the 1980s–1990s, but subsequently, “the indices have returned to close to their long-term mean.” Barring and von Storch

7.7.5 Wind

Differences in pressure, or pressure gradients, cause wind. How, then, does wind respond to rising temperatures? Several studies have addressed different aspects of this question in recent years.

conclude their storminess proxies “show no indication of a long-term robust change towards a more vigorous storm climate.” In fact, during “the entire historical period,” they write, storminess was “remarkably stable, with no systematic change and little transient variability.”

Contemporaneously, Hanna *et al.* (2004) examined several climatic variables, including air pressure, temperature, precipitation, and sunshine data, over the past century in Iceland, to determine whether there is “possible evidence of recent climatic changes” in that cold island nation. For the period 1820–2002, annual and monthly pressure data exhibited semi-decadal oscillations but no significant upward or downward trend. As for what may be responsible for the oscillations in the data, they mention the likely influence of the Sun, noting a 12-year peak in their spectral analysis of the pressure data is “suggestive of solar activity.”

Expanding the solar/pressure link further, Veretenenko *et al.* (2005) examined the potential influence of galactic cosmic rays (GCR) on the long-term variation of North Atlantic sea-level pressure over the period 1874–1995. Comparisons of long-term variations in cold-season (October–March) sea-level pressure with different solar/geophysical indices revealed increasing sea-level pressure coincided with a secular rise in solar/geomagnetic activity accompanied by a decrease in GCR intensity, whereas long-term decreases in sea-level pressure were observed during periods of decreasing solar activity and rising GCR flux. Spectral analysis further supported a link between sea-level pressure, solar/geomagnetic activity, and GCR flux, as similar spectral characteristics (periodicities) were present among all datasets at time scales ranging from approximately 10 to 100 years.

The results of this analysis support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. As to how this relationship works, Veretenenko *et al.* hypothesize GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development.

Gulev and Grigorieva (2004) used the Voluntary Observing Ship wave data of Worley *et al.* (2005) to characterize significant wind-driven wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists

report “the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950,” which appears to vindicate the IPCC’s thoughts on the subject. “However,” they continue, “for the period 1885–2002 there is no secular trend in HS in the Atlantic,” and “the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002.”

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century “is comparable with that for recent decades,” and “in the Atlantic it is even higher than during the last 5 decades.” In the Atlantic the mean HS of the entire decade of the 1920s is higher than that of any recent decade; and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes us from conclusively proving this latter point. Given such findings, it is clear annual mean wind-driven wave heights over the last decade of the twentieth century were not higher than those that occurred earlier in the century.

McVicar *et al.* (2010) note there has been great interest “in the widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years,” citing the work of Roderick *et al.* (2007), McVicar *et al.* (2008), Pryor *et al.* (2009), and Jiang *et al.* (2010). They state this *stilling*, as it has come to be called, is “a key factor in reducing atmospheric evaporative demand,” which drives actual evapotranspiration when water availability is not limiting, as in the case of lakes and rivers. In addition, they note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases, as demonstrated by the work of McVicar *et al.* (2007). Increasing wind speeds lead to increases in atmospheric evaporative demand, whereas decreasing wind speeds do the opposite, and both of these changes can be of great significance for people dependent upon water resources derived from mountainous headwater catchments. It would be advantageous to learn how the change in near-surface wind speed with ground elevation may have varied over the last few decades of global warming, since, as the authors note, “over half the global population live in catchments with rivers originating in mountainous regions (Beniston, 2005), with this water supporting about 25% of the

global gross domestic product (Barnett *et al.*, 2005)."

Defining uz as change in wind speed with change in elevation ($uz = \Delta u / \Delta z$, where $\Delta u = u_2 - u_1$, $\Delta z = z_2 - z_1$, and $z_2 > z_1$), McVicar *et al.* calculated monthly averages of uz based on monthly average u data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China and by MeteoSwiss at 37 sites in Switzerland from January 1960 through December 2006. The authors report their research constituted "the first time that long-term trends in uz in mountainous regions have been calculated." The seven scientists found, "for both regions uz trend results showed that u has declined more rapidly at higher than lower elevations." Such a decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations should act to reduce water loss via evaporation from high-altitude catchments in many of the world's mountainous regions, providing more water for people who obtain it from such sources. McVicar *et al.* note the "reductions in wind speed will serve to reduce rates of actual evapotranspiration partially compensating for increases in actual evapotranspiration due to increasing air temperatures."

More recently, Alexander *et al.* (2011) analyzed storminess across the whole of southeast (SE) Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century. According to the four researchers, their results "show strong evidence for a significant reduction in intense wind events across SE Australia over the past century." More specifically, "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease." "In terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Ekman (1999) utilized a sea-level record beginning in 1774 from Stockholm, Sweden to investigate long-term trends in the levels of the Baltic and North Seas and the relationships of these trends to various climatic factors. They determined there had been throughout the 1800s a rapidly decreasing number of dominating winter winds from the northeast. Since such winds typically tend to reduce sea levels at Stockholm, this regime shift led to a gradual increase in the rate of rise of sea level there. Subsequently, the winter winds gradually shifted to

where the dominant airflow was from the southwest. Since winds from this direction tend to promote high sea levels at Stockholm, the rate of rise in sea level there continued to increase. The net result of these wind regime changes was thus a continual increase in the rate of rise of sea level at Stockholm over the entire two-century period, resulting in a mean sea-level rise of 1.0 mm/year over the twentieth century. Thus, as the world transitioned from the Little Ice Age to the Modern Warm Period, sea levels around Stockholm rose, not from the melting of polar ice but from a systematic shifting of wind direction.

In another study from Sweden, cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen), were examined by Björck and Clemmensen (2004) for their content of wind-transported clastic material, to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter wind climate in that part of the world. The researchers report, "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," and "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

Björck and Clemmensen also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they state an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)," and they find a period of high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting this period coincides with the Spörer Minimum of AD 1420–1530. They note the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Clarke *et al.* (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, identifying three main phases of wind-induced dune formation: 4,000–3,000 years ago during the long cold interval that preceded the Roman Warm Period; 1,300–900 years ago during the early to middle Medieval Warm Period, but during what they describe as its cooler periods; and 550–250 years ago during the Little Ice Age, again during what they call its cooler periods. In addition, a search of the literature allowed the scientists to identify similar massive wind-induced movements of sand in England, Scotland, Denmark, Portugal, and the Netherlands during these periods of relative coolness. For the most recent of these cool periods, they also note the existence of voluminous historical records that describe many severe North Atlantic wind storms.

Working with insurance industry data, Changnon (2009) analyzed “catastrophes caused solely by high winds” that had had their losses adjusted so as to make them “comparable to current year [2006] values.” Although the average monetary loss of each year’s catastrophes “had an upward linear trend over time, statistically significant at the 2% level,” when the number of each year’s catastrophes was considered, it was found “low values occurred in the early years (1952–1966) and in later years (1977–2006),” and “the peak of incidences came during 1977–1991.” Changnon reports “the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend.”

Two years later in a similar study, Changnon (2011) calculated trends in a number of straight-line wind-related parameters over the period 1950–2006. According to the Illinois State Water Survey researcher, high winds—excluding those associated with hurricanes, tornadoes, snowstorms, blizzards, and heavy rainstorms—are one of the United States’ leading types of damage-producing storms. These straight-line windstorms, as they are called, produce annual U.S. property and crop losses totaling \$380 million and rank as the nation’s sixth-most-damaging type of severe weather.

With respect to whether the global warming of the past half-century has had any significant effect on straight-line windstorm frequency or ferocity, Changnon notes “the distribution of losses over time showed high values in recent years, 1997–2006, and the 55-year distribution had a statistically significant upward trend over time.” However, he further describes how a number of adjustments to loss data of

the past needed to be made “to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current year values, 2006 in this study.” When these adjustments were made, he reports the 55-year time trend “was not up or down.” He finds “the national temporal distribution of catastrophic windstorms during 1952–2006 has a flat trend,” suggesting, the global warming of the past half-century or so has had no noticeable impact on the net frequency or ferocity of straight-line windstorms in the United States.

The research summarized here suggests the cool nodes of Earth’s millennial-scale climatic oscillation are more prone to high wind conditions than are its warm nodes, and the gradual warming of the globe over the past two centuries has probably reduced wind speeds over many portions of the planet, although there may be regional exceptions. In addition, changes in wind speed have implications for a host of other phenomena, from reconstructions of sea-level histories to fluctuations in evaporation and wave heights. Finally, there is some evidence these wind-driven phenomena may be solar-induced.

References

- Alexander, L.V., Wang, X.L., Wan, H., and Trewin, B. 2011. Significant decline in storminess over southeast Australia since the late 19th century. *Australian Meteorological and Oceanographic Journal* **61**: 23–30.
- Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**: 303–309.
- Barring L. and von Storch, H. 2004. Scandinavian storminess since about 1800. *Geophysical Research Letters* **31**: 10.1029/2004GL020441.
- Beniston, M. 2005. Mountain climates and climatic change: An overview of processes focusing on the European Alps. *Pure and Applied Geophysics* **162**: 1587–1606.
- Björck, S. and Clemmensen, L.B. 2004. Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene* **14**: 677–688.
- Changnon, S.A. 2009. Temporal and spatial distributions of wind storm damages in the United States. *Climatic Change* **94**: 473–482.
- Changnon, S.A. 2011. Windstorms in the United States. *Natural Hazards* **59**: 1175–1187.

Observations: Extreme Weather

Clarke, M., Rendell, H., Tastet, J-P., Clave, B., and Masse, L. 2002. Late-Holocene sand invasion and North Atlantic storminess along the Aquitaine Coast, southwest France. *The Holocene* **12**: 231–238.

Ekman, M. 1999. Climate changes detected through the world's longest sea level series. *Global and Planetary Change* **21**: 215–224.

Gulev, S.K. and Grigorieva, V. 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research Letters* **31**: 10.1029/2004GL021040.

Hanna, H., Jónsson, T., and Box, J.E. 2004. An analysis of Icelandic climate since the nineteenth century. *International Journal of Climatology* **24**: 1193–1210.

Jiang, Y., Luo, Y., Zhao, Z., and Tao, S. 2010. Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology* **99**: 421–430.

McPhaden, M.J. and Zhang, D. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature* **415**: 603–608.

McVicar, T.R., Van Niel, T.G., Li, L.T., Hutchinson, M.F., Mu, X.-M., and Liu, Z.-H. 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology* **338**: 196–220.

McVicar, T.R., Van Niel, T.G., Li, L.T., Roderick, M.L., Rayner, D.P., Ricciardulli, L., and Donohue, R.G. 2008. Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters* **35**: 10.1029/2008GL035627.

McVicar, T.R., Van Niel, T.G., Roderick, M.L., Li, L.T., Mo, X.G., Zimmermann, N.E., and Schmatz, D.R. 2010. Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960–2006. *Geophysical Research Letters* **37**: 10.1029/2009GL042255.

Pirazzoli, P.A. 2000. Surges, atmospheric pressure and wind change and flooding probability on the Atlantic coast of France. *Oceanologica Acta* **23**: 643–661.

Pryor, S.C., Barthelmie, R.J., Young, D.T., Takle, E.S., Arritt, R.W., Flory, D., Gutowski Jr., W.J., Nunes, A., and Roads, J. 2009. Wind speed trends over the contiguous United States. *Journal of Geophysical Research* **114**: 10.1029/2008JD011416.

Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., and Hobbins, M.T. 2007. On the attribution of changing pan evaporation. *Geophysical Research Letters* **34**: 10.1029/2007GL031166.

Siegismund, F. and Schrum, C. 2001. Decadal changes in the wind forcing over the North Sea. *Climate Research* **18**: 39–45.

Slonosky, V.C., Jones, P.D., and Davies, T.D. 2000. Variability of the surface atmospheric circulation over Europe, 1774–1995. *International Journal of Climatology* **20**: 1875–1897.

Veretenenko, S.V., Dergachev, V.A., and Dmitriyev, P.B. 2005. Long-term variations of the surface pressure in the North Atlantic and possible association with solar activity and galactic cosmic rays. *Advances in Space Research* **35**: 484–490.

Worley, S.J., Woodruff, S.D., Reynolds, R.W., Lubker, S.J., and Lott, N. 2005. ICOADS release 2.1 data and products. *International Journal of Climatology* **25**: 823–842.

7.8 Hurricanes

For many years, nearly all climate model output suggested tropical cyclones (TC) should become both more frequent and more intense as planetary temperatures rise. As a result of such projections, scientists worked to improve the temporal histories of these particular TC characteristics for various ocean basins around the world in an effort to evaluate the plausibility of such projections. In nearly all instances, the research revealed TCs have not been increasing in frequency or magnitude during the era of modern instrumentation and rise of atmospheric CO₂.

As a result of these findings, the IPCC revised its conclusion on hurricanes, stating in its most recent report, “recent re-assessments of tropical cyclone data do not support the [Fourth Assessment Report] conclusions of an increase in the most intense tropical cyclones or an upward trend in the potential destructiveness of all storms since the 1970s. There is low confidence that any reported long-term changes are robust, after accounting for past changes in observing capabilities.”

Not willing to disavow the model projection fully, the IPCC adds, “over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust” (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, despite the vast array of observational data that do not support the model projections, the IPCC continues to project future increases in certain TC parameters for the globe (increase in TC intensity) and for individual ocean basins (increase in the number of intense storms):

Projections for the 21st century indicate that it is likely that the global frequency of tropical

cyclones will either decrease or remain essentially unchanged, concurrent with a likely global increase in both tropical cyclone maximum wind speed and rainfall rates, but there is lower confidence in region-specific projections. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 59).

... it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates ... It is more likely than not that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 62).

In light of the IPCCs continued claims regarding hurricanes, Section 7.10 reviews the scientific literature to present a detailed examination of what has been learned with respect to such storms in various ocean basins across the globe. The results of that examination reveal real-world data do not support, and in fact essentially invalidate, the model claims. Global warming, whether CO₂-induced or natural, is likely to have no measurable influence on the frequency or intensity of tropical cyclones.

7.8.1 Atlantic Ocean

Data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Atlantic Ocean.

7.8.1.1 Frequency

7.8.1.1.1 The Past Century

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what the IPCC describes as unprecedented global warming?

In an early attempt to answer this question, Bove *et al.* (1998) examined the characteristics of all recorded landfalling U.S. Gulf Coast hurricanes—defined as those whose eyes made landfall between Cape Sable, Florida and Brownsville, Texas—from

1896 to 1995. They found the first half of this period saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade, and the same was true for intense hurricanes of category 3 or more on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes both trended downward from 1966 to the end of the period investigated, with the decade 1986–1995 exhibiting the fewest intense hurricanes of the century. The three researchers conclude, “fears of increased hurricane activity in the Gulf of Mexico are premature.”

Noting the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but during the preceding four years (1991–1994) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al.* (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. They found “perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region.” They also note, “in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea level pressure, abnormally warm ocean waters, and very humid values of total precipitable water.”

The enhanced activity of the 1995 Atlantic hurricane season also may have been affected by the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Most important, perhaps, was what Landsea *et al.* called the “dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions,” which contributed to what they described as “the dramatic reversal” of weather characteristics “which dominated during the [prior] four hurricane seasons.”

The four researchers note, “Some have asked whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic ‘greenhouse’ gases.” They concluded “such an interpretation is not warranted,” because the factors noted above seem sufficient to explain the observations. “Additionally,” they write, “Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean

Observations: Extreme Weather

intensity of all named storms over the past few decades,” and “this holds true even with the inclusion of 1995’s Atlantic hurricane season.”

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al.* (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944–1996, decreasing trends were found for the total number of hurricanes, the number of intense hurricanes, the annual number of hurricane days, the maximum attained wind speed of all hurricane storms averaged over the course of a year, and the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they report the total number of Atlantic hurricanes making landfall in the United States decreased over the 1899–1996 time period, and normalized trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of \$728 million per decade.

Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States during the period 1935–1998. They found “a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of -0.011 ± 0.0086 storms per year.” They expressly note “the estimated trend slope is negative,” meaning the yearly number of such storms is decreasing, just the opposite of what they described as the “frequent hypothesis ... that global warming is causing increased storm activity.” Their statistical analysis indicates “the trend slope is not significantly different from zero.”

Easterling *et al.* (2000) point out the mean temperature of the globe rose by about 0.6°C over the past century. They looked for possible impacts of this phenomenon on extreme weather events, which if found to be increasing, “would add to the body of evidence that there is a discernible human affect on the climate.” Their search revealed few changes of significance, although they did determine “the number of intense and landfalling Atlantic hurricanes has declined.”

Balling and Cervený (2003) wrote, “many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones,” but they note empirical studies had failed to reveal any such

relationships. They also note “some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events,” and these relationships have not been thoroughly studied with historical real-world data.

The two Arizona State University climatologists constructed a daily database of tropical storms that occurred in the Caribbean Sea, Gulf of Mexico, and western North Atlantic Ocean over the period 1950–2002, generating “a variety of parameters dealing with duration, timing, and location of storm season,” after which they tested for trends in these characteristics, attempting to explain the observed variances in the variables using regional, hemispheric, and global temperatures. They “found no trends related to timing and duration of the hurricane season and geographic position of storms in the Caribbean Sea, Gulf of Mexico and tropical sector of the western North Atlantic Ocean.” They also “could find no significant trends in these variables and generally no association with them and the local ocean, hemispheric, and global temperatures.”

Elsner *et al.* (2004) conducted a changepoint analysis of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the twentieth century. This technique, they write, “quantitatively identifies temporal shifts in the mean value of the observations.” Their work revealed “major North Atlantic hurricanes have become more frequent since 1995,” but at “a level reminiscent of the 1940s and 1950s.” That appears to be an overstatement of their findings; their data indicate the mean annual hurricane count for the seven-year period 1995–2001 was 3.86, while the mean count for the 14-year period 1948–1961 was 4.14. They also report, “in general, twentieth-century U.S. hurricane activity shows no abrupt shifts,” noting there was an exception over Florida, “where activity decreased during the early 1950s and again during the late 1960s.” They also found “El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida.”

Elsner *et al.*’s work contradicts the claim that global warming leads to more intense hurricane activity. North Atlantic hurricane activity did not increase over the twentieth century, during which the IPCC says Earth experienced a temperature increase unprecedented over the past two millennia. Moreover, hurricane activity also did not increase, and in fact decreased, in response to the more sporadic warming

associated with periodic El Niño conditions.

Virmani and Weisberg (2006) report “the 2005 hurricane season saw an unprecedented number of named tropical storms since records began in 1851.” Moreover, they note it followed “on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path.” They wondered whether the increased hurricane activity occurred in response to recent global warming or if it bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

The two researchers determined “latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea level pressure,” which “resulted in anomalously high sea surface temperatures” that “contributed to earlier and more intense hurricanes in 2005.” They note “these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998.” In addition, they found no “clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation.” It would appear the 2005 hurricane season was not as unusual as many people have made it out to be, and there is no compelling reason to ascribe whatever degree of uniqueness it may have possessed to recent global warming.

Mann and Emanuel (2006) used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871–2005, and Holland and Webster (2007) analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both papers linked these changes to anthropogenic greenhouse warming.

In a compelling rebuttal of these conclusions, Landsea (2007) cited a number of possible biases in the cyclone frequency trends derived in the two studies, concluding “improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones.”

Parisi and Lund (2008) calculated return periods of Atlantic-basin U.S. landfalling hurricanes based on “historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques” for each of the categories (1–5) of the Saffir-Simpson Hurricane Scale. Return periods, in ascending Saffir-Simpson Scale category order, were 0.9 years for category 1, 1.3 years for category 2, 2.0 years for category 3, 4.7 years for category 4, and 23.1 years for category 5 hurricanes. In addition, the two researchers reported corresponding non-encounter probabilities in any one hurricane season were calculated to be (category 1) 0.17, (category 2) 0.37, (category 3) 0.55, (category 4) 0.78, and (category 5) 0.95. The hypothesis that U.S. hurricane strike frequencies are “increasing in time”—which is often stated as fact—is “statistically rejected,” they conclude.

Chylek and Lesins (2008) applied “simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity and other features of interest.” Using a hurricane activity index that integrates hurricane numbers, durations, and strengths, the two researchers report discovering “a quasi-periodic behavior with a period around 60 years superimposed upon a linearly increasing background.” However, they note “the linearly increasing background is significantly reduced or removed when various corrections were applied for hurricane undercounting in the early portion of the record.” Further noting “the last minimum in hurricane activity occurred around 1980,” Chylek and Lesins compared the two 28-year-long periods on either side of this date, finding “a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification.” They conclude, “if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60-year quasi-periodic cycle.”

Klotzbach and Gray (2008) employed sea surface temperature (SST) data for the far North Atlantic (50–60°N, 50–10°W) and sea-level pressure (SLP) data for the North Atlantic (0–50°N, 70–10°W) to construct an index of the Atlantic Multidecadal Oscillation (AMO), which they defined as the difference between the standardized SST and SLP anomalies (SST-SLP) for the hurricane season of June–November, and which they evaluated for the period 1878–2006. They compared their results, to which they applied a 1-2-3-

Observations: Extreme Weather

2-1 filter, with a number of hurricane properties.

Klotzbach and Gray's analysis revealed the existence of three positive and two negative AMO phases over the period of their study, as illustrated in Figure 7.8.1.1.1.

Zeng *et al.* (2009) “synthesized field measurements, satellite image analyses, and empirical models to evaluate forest and carbon cycle impacts for historical tropical cyclones from 1851 to 2000 over the continental U.S.” They found greater forest

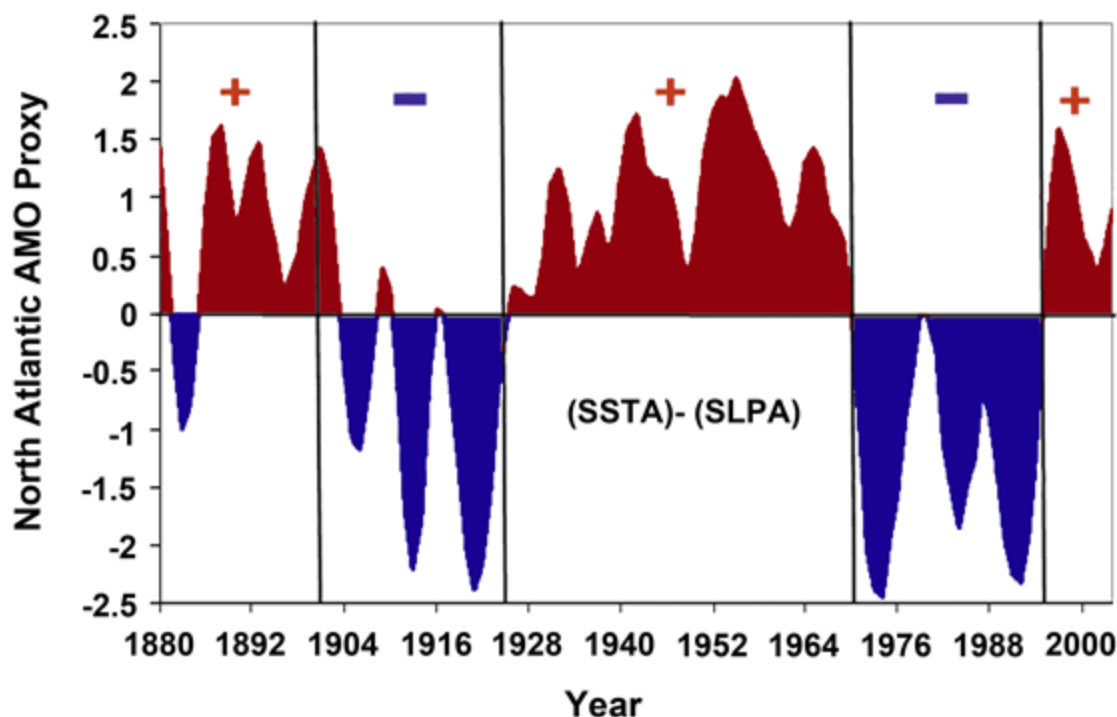


Figure 7.8.1.1.1. North Atlantic AMO Index. Adapted from Klotzbach, P.J. and Gray, W.M. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate* 21: 3929-3935.

In comparing annually averaged results for tropical cyclone characteristics between the positive and negative AMO phases indicated in the figure, it can be calculated from the tropical cyclone data of the authors that the positive-AMO-phase to negative-AMO-phase ratios of hurricane numbers, hurricane days, major hurricane numbers, and major hurricane days were 1.53, 1.89, 2.00, and 2.46, respectively, over the period studied. For the 20 most positive and 20 most negative AMO years, those ratios, in the same order, were 1.73, 2.41, 2.80, and 4.94. Such calculations demonstrate the North Atlantic AMO is tremendously important to hurricane genesis and development, and this striking natural variability makes it extremely difficult to determine whether there is any long-term trend in the tropical cyclone data that might be attributable to twentieth century global warming.

impacts and biomass loss between 1851 and 1900 from hurricane activity than during the twentieth century. On average, the authors found “147 million trees were affected each year between 1851 and 1900,” which led to “a 79-Tg annual biomass loss.” Average annual forest impact and biomass loss between 1900 and 2000 “were 72 million trees and 39 Tg, which were only half of the impacts before 1900.” The authors say these results are in “accordance with historical records showing that Atlantic tropical cyclones were more active during the period from 1870 to 1900.” They also note the amount of carbon released from the downed and damaged trees “reached a maximum value in 1896, after which it continuously decreased until 1978,” when it leveled off for the remaining two decades of the twentieth century.

Hagen and Landsea (2012) point out “previous

studies state that there has been an increase in the number of intense hurricanes and [they] attribute this increase to anthropogenic global warming,” but “other studies claim that the apparent increased hurricane activity is an artifact of better observational capabilities and improved technology for detecting these intense hurricanes.” They focused their research on the ten most recent Category 5 hurricanes known to have occurred in the Atlantic Ocean, from Hurricane Andrew in 1992 to Hurricane Felix of 2007. Placing these ten hurricanes into the context of the technology available from 1944 to 1953—the first decade of aircraft reconnaissance—they determined how many of these Category 5 hurricanes likely would have been recorded as Category 5 if they had occurred during the earlier period, using only the observations likely to have been available with then-existing technology and observational networks.

The two U.S. researchers report “there are likely to have been several Category 4 and 5 hurricanes misclassified as being weaker prior to the satellite era.” For example, “if the ten most recent Category 5 hurricanes occurred during the late-1940s period, only two of them would be considered Category 5 hurricanes (and three of ten for the early-1950s period).” In addition, “three recent Category 4 hurricanes were identified that would likely not have been counted as major hurricanes if they had occurred during the late 1940s/1950s.” Hagen and Landsea conclude, “counts of Category 4 and 5 hurricanes (at least through 1953 and likely beyond that year) are not nearly as reliable as they are today.” They further conclude “future studies that discuss frequency trends of Atlantic basin Category 4 and 5 hurricanes must take into account the undercount biases that existed prior to the geostationary satellite era due to the inability to observe these extreme conditions.”

Villarini *et al.* (2011) used the statistical model developed by Villarini *et al.* (2010), in which “the frequency of North Atlantic tropical storms is modeled by a conditional Poisson distribution with a rate of occurrence parameter that is a function of tropical Atlantic and mean tropical sea surface temperatures (SSTs),” to examine “the impact of different climate models and climate change scenarios on North Atlantic and U.S. landfalling tropical storm activity,” and reconcile “differing model projections of changes in the frequency of North Atlantic tropical storms in a warmer climate.”

The five researchers report their results “do not support the notion of large increases in tropical storm frequency in the North Atlantic basin over the twenty-

first century in response to increasing greenhouse gases.” They also note “the disagreement among published results concerning increasing or decreasing North Atlantic tropical storm trends in a warmer climate can be largely explained (close to half of the variance) in terms of the different SST projections (Atlantic minus tropical mean) of the different climate model projections.”

They also find, “for the SRES A1B scenario and 24 climate models, over the twenty-first century there is a large spread among projected trends in tropical storm activity in the North Atlantic basin, with a mean of -0.83 tropical storm per century and a standard deviation of 2.48 tropical storms per century.” And with respect to U.S. land-falling tropical storms, they state, “results based on 7 climate models point to a statistically significant increasing trend, while 6 point to a decreasing trend,” suggesting the models are inconsistent in projecting what will happen over the current century. Villarini *et al.* (2011) conclude, among other things, “there is a considerable level of uncertainty in climate change projections that will remain effectively ‘irreducible,’ as no current prospects exist for skillful century-scale predictions of unforced climate variability.”

References

- Balling Jr., R.C. and Cervený, R.S. 2003. Analysis of the duration, seasonal timing, and location of North Atlantic tropical cyclones: 1950-2002. *Geophysical Research Letters* **30**: 10.1029/2003GL018404.
- Bove, M.C., Zierden, D.F., and O’Brien, J.J. 1998. Are gulf landfalling hurricanes getting stronger? *Bulletin of the American Meteorological Society* **79**: 1327–1328.
- Chylek, P. and Lesins, G. 2008. Multidecadal variability of Atlantic hurricane activity: 1851–2007. *Journal of Geophysical Research* **113**: 10.1029/2008JD010036.
- Easterling, D.R., Evans, J.L., Groisman, P. Ya., Karl, T.R., Kunkel, K.E., and Ambenje, P. 2000. Observed variability and trends in extreme climate events: A brief review. *Bulletin of the American Meteorological Society* **81**: 417–425.
- Elsner, J.B., Niu, X., and Jagger, T.H. 2004. Detecting shifts in hurricane rates using a Markov Chain Monte Carlo approach. *Journal of Climate* **17**: 2652–2666.
- Hagen, A.B. and Landsea, C.W. 2012. On the classification of extreme Atlantic hurricanes utilizing mid-twentieth-century monitoring capabilities. *Journal of Climate* **25**: 4461–4475.

Holland, G.J. and Webster, P.J. 2007. Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philosophical Transactions of the Royal Society of London, Series A* **365**: 10.1098/rsta.2007.2083.

Klotzbach, P.J. and Gray, W.M. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate* **21**: 3929–3935.

Landsea, C.W. 2007. Counting Atlantic tropical cyclones back to 1900. *EOS, Transactions, American Geophysical Union* **88**: 197, 202.

Landsea, C.W., Bell, G.D., Gray, W.M., and Goldenberg, S.B. 1998. The extremely active 1995 Atlantic hurricane season: environmental conditions and verification of seasonal forecasts. *Monthly Weather Review* **126**: 1174–1193.

Landsea, C.N., Pielke Jr., R.A., Mestas-Núñez, A.M., and Knaff, J.A. 1999. Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change* **42**: 89–129.

Mann, M. and Emanuel, K. 2006. Atlantic hurricane trends linked to climate change. *EOS, Transactions, American Geophysical Union* **87**: 233, 238, 241.

Parisi, F. and Lund, R. 2000. Seasonality and return periods of landfalling Atlantic basin hurricanes. *Australian & New Zealand Journal of Statistics* **42**: 271–282.

Parisi, F. and Lund, R. 2008. Return periods of continental U.S. hurricanes. *Journal of Climate* **21**: 403–410.

Villarini, G., Vecchi, G.A., Knutson, T.R., Zhao, M., and Smith, J.A. 2011. North Atlantic tropical storm frequency response to anthropogenic forcing: Projections and sources of uncertainty. *Journal of Climate* **24**: 3224–3238.

Villarini, G., Vecchi, G.A., and Smith, J.A. 2010. Modeling of the dependence of tropical storm counts in the North Atlantic basin on climate indices. *Monthly Weather Review* **138**: 2681–2705.

Virmani, J.I. and Weisberg, R.H. 2006. The 2005 hurricane season: An echo of the past or a harbinger of the future? *Geophysical Research Letters* **33**: 10.1029/2005GL025517.

Zeng, H., Chambers, J.Q., Negron-Juarez, R.I., Hurr, G.C., Baker, D.B., and Powell, M.D. 2009. Impacts of tropical cyclones on U.S. forest tree mortality and carbon flux from 1851 to 2000. *Proceedings of the National Academy of Sciences USA* **106**: 7888–7892.

7.8.1.1.2 The Past Few Centuries

Has the warming of the past century, which rescued the world from the extreme cold of the Little Ice Age, led to the formation of more numerous Atlantic Basin

tropical storms and hurricanes? Several studies have broached this question with sufficiently long data records to provide reliable answers.

Elsner *et al.* (2000) provided a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales, and they presented data on major hurricane occurrences in 50-year intervals for Bermuda, Jamaica, and Puerto Rico. These data reveal hurricanes occurred at far lower frequencies in the last half of the twentieth century than they did in the preceding five 50-year periods at all three of the locations studied. From 1701 to 1850, for example, when Earth was in the grip of the Little Ice Age, major hurricane frequency was 2.77 times greater at Bermuda, Jamaica, and Puerto Rico than it was from 1951 to 1998. From 1851 to 1950, when the planet was in transition from the Little Ice Age to current conditions, the three locations experienced a mean hurricane frequency 2.15 times greater than what they experienced from 1951 to 1998.

Such findings for the Caribbean Sea were echoed by Elsner (2008) in his summary of the *International Summit on Hurricanes and Climate Change* held in May 2007. He states paleotempestology—which he defines as the study of prehistoric storms based on geological and biological evidence—indicates the presence of more hurricanes in the northeastern Caribbean Sea “during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today.” He goes on to say his work provides evidence that “today’s warmth is not needed for increased storminess.”

In another multicentury study, Boose *et al.* (2001) used historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They find “no clear century-scale trend in the number of major hurricanes.” At lower damage levels, fewer hurricanes were recorded in the seventeenth and eighteenth centuries than in the nineteenth and twentieth centuries, but the three researchers conclude “this difference is probably the result of improvements in meteorological observations and records since the early 19th century.” With the better records of the past 200 years, it is clear the cooler nineteenth century had five of the highest-damage storms, whereas the warmer twentieth century had only one such storm.

Nyberg *et al.* (2007) developed a history of major (Category 3–5) Atlantic hurricanes over the past 270 years based on proxy records of vertical wind shear

and sea surface temperature derived from corals and a marine sediment core. Wind shear and SST are the primary controlling forces for the formation of major hurricanes in the region west of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10°N and 20°N, where 85% of all major hurricanes and 60% of all non-major hurricanes and tropical storms of the Atlantic are formed.

The researchers discovered the average frequency of major Atlantic hurricanes “decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s.” They note “a gradual downward trend is evident from an average of ~4.1 (1775–1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s,” and “the current active phase (1995–2005) is unexceptional compared to the other high-activity periods of ~1756–1774, 1780–1785, 1801–1812, 1840–1850, 1873–1890 and 1928–1933.” They conclude the recent ratcheting up of Atlantic major hurricane activity appears to be simply “a recovery to normal hurricane activity.” In a commentary on Nyberg *et al.*’s paper, Elsner (2007) stated “the assumption that hurricanes are simply passive responders to climate change should be challenged,” which Nyberg *et al.* do convincingly.

Also noting “global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean,” with the implication that “a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State,” Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration’s Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005.

The work revealed “a total of 76 storms of tropical origin passed over New York State between 1851 and 2005,” and of these storms, “14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms.” For Long Island, he reports “the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively.” He finds storm activity was greatest in both the late nineteenth century and the late twentieth century, and “the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century.” Vermette concludes, “rather than a linear change, that may be associated with a global warming, the changes in recent time are following a

multidecadal cycle and returning to conditions of the latter half of the 19th century.”

Mock (2008) developed a “unique documentary reconstruction of tropical cyclones for Louisiana, USA, that extends continuously back to 1799 for tropical cyclones and to 1779 for hurricanes.” Mock says this record, derived from daily newspaper accounts, private diaries, plantation diaries, journals, letters, and ship records and augmented “with the North Atlantic hurricane database as it pertains to all Louisiana tropical cyclones up through 2007,” is “the longest continuous tropical cyclone reconstruction conducted to date for the United States Gulf Coast.” The record reveals “the 1820s/early 1830s and the early 1860s are the most active periods for the entire record.”

The University of South Carolina researcher says “the modern records which cover just a little over a hundred years [are] too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude.” He states, “if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [those storms] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005.”

Chenoweth and Divine (2008) examined newspaper accounts, ships’ logbooks, meteorological journals, and other documents to reconstruct a history of tropical cyclones passing through the 61.5°W meridian between the coast of South America (~9.7°N) and 25.0°N over the period 1690–2007, which they describe as “the longest and most complete record for any area of the world.” The two authors found “no evidence of statistically significant trend in the number of tropical cyclones passing through the region on any time scale.” They also note “hurricane frequency is down about 20% in the 20th century compared to earlier centuries,” and “this decline is consistent with the 20th century observed record of decreasing hurricane landfall rates in the U.S. (Landsea *et al.*, 1999; Elsner *et al.*, 2004) and proxy reconstruction of higher tropical cyclone frequency in Puerto Rico before the 20th century (Nyberg *et al.*, 2007), as well as model-simulated small changes in Atlantic basin tropical cyclone numbers in a doubled CO₂ environment (Emanuel *et al.*, 2008; Knutson *et al.*, 2008).” In addition, they report “the period 1968–1977 was probably the most inactive period since the islands were settled in the 1620s and 1630s,” which, in their words, “supports

the results of Nyberg *et al.* (2007) of unprecedented low frequency of major hurricanes in the 1970s and 1980s.”

Following up on their work four years later, Chenoweth and Divine (2012) examined the records employed in their earlier paper in more detail, determining “the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian.” Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends.

Chenoweth and Divine report their record of tropical cyclone activity “reveals no trends in LACE in the best-sampled regions for the past 320 years,” and “even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or LACE,” noting these results are similar to those reported earlier by them (Chenoweth and Divine, 2008) on tropical cyclone counts. In addition, they indicate LACE along the 61.5°W meridian is “highly correlated” with Atlantic-Basin-wide ACE.

Wang and Lee (2008) used the “improved extended reconstructed” sea surface temperature (SST) data described by Smith and Reynolds (2004) for the period 1854–2006 to examine historical temperature changes over the global ocean, after which they regressed vertical wind shear—“calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data”—onto a temporal variation of global warming defined by the SST data. They discovered warming of the surface of the global ocean is typically associated with a secular increase of tropospheric vertical wind shear in the main development region (MDR) for Atlantic hurricanes, and the long-term increased wind shear of that region has coincided with a weak but robust downward trend in U.S. landfalling hurricanes. However, this relationship has a pattern to it, whereby local ocean warming in the Atlantic MDR reduces the vertical wind shear there, whereas “warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes.”

The two researchers conclude “the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes” to date, “warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes.” As for the future, they write, “whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans.”

Vecchi and Knutson (2008) point out “there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency.” They derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) missed by the observing system in the pre-satellite era (1878–1965), after which they analyzed trends of reconstructed TC numbers and duration over various time periods and assessed whether those trends might have been related to trends in sea surface temperature over the main development region of North Atlantic TCs.

Vecchi and Knutson found “the estimated trend for 1900–2006 is highly significant (+~4.2 storms century⁻¹)” but “strongly influenced by a minimum in 1910–30, perhaps artificially enhancing significance.” When using their base case adjustment for missed TCs and considering the entire 1878–2006 record, they find the trend in the number of TCs is only “weakly positive” and “not statistically significant,” and they note the trend in average TC duration over the 1878–2006 period “is negative and highly significant.”

Similar shortcomings in the observational record have been reported by other researchers. Landsea *et al.* (2010) note “records of Atlantic basin tropical cyclones (TCs) since the late nineteenth century indicate a very large upward trend in storm frequency,” and they state this increase in documented TCs “has been previously interpreted as resulting from anthropogenic climate change.” The note “improvements in observing and recording practices provide an alternative interpretation for these changes” and report “recent studies suggest that the number of potentially missed TCs is sufficient to explain a large part of the recorded increase in TC counts.”

Landsea *et al.* explored the influence of another factor—TC duration—on observed changes in TC

frequency, working with the widely used Atlantic hurricane database known as HURDAT. They found the occurrence of short-lived storms of two days duration or less had increased dramatically, from less than one per year in the late nineteenth and early twentieth centuries to about five per year since about AD 2000, whereas numbers of medium- to long-lived storms had increased “little, if at all.” They conclude the previously documented increase in total TC frequency since the late nineteenth century in the database was “primarily due to an increase in very short-lived TCs.”

Landsea *et al.* next conducted a sampling study based on the distribution of ship observations, which provided quantitative estimates of the frequency of missed TCs with durations exceeding two days. Upon adding the estimated numbers of missed TCs to the time series of moderate and long-lived Atlantic TCs, they found “neither time series exhibits a significant trend since the late nineteenth century.”

Landsea *et al.* conclude sub-sampling of TCs back in time will artificially introduce increases in a wide array of TC characteristics, including “frequency of hurricanes and major hurricanes, duration of TCs, length of season, peak intensity, and integrated TC measures [like Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI)],” which they say “should not be used directly from HURDAT for climate variability and change studies without consideration of, or quantitatively accounting for, how observational network alterations are affecting these statistics.”

Vecchi and Knutson (2011) conducted a new analysis of the characteristics of Atlantic hurricanes whose peak winds exceeded 33 m/s for the period 1878–2008, based on the HURDAT database, developing a new estimate of the number of hurricanes that occurred in the pre-satellite era (1878–1965) based on analyses of TC storm tracks and the geographical distribution of the tracks of the ships that reported TC encounters. The two researchers report “both the adjusted and unadjusted basin-wide hurricane data indicate the existence of strong interannual and decadal swings.” Although “existing records of Atlantic hurricanes show a substantial increase since the late 1800s,” their analysis suggests “this increase could have been due to increased observational capability.” They write, “after adjusting for an estimated number of ‘missed’ hurricanes (including hurricanes that likely would have been miss-classified as tropical storms), the secular change since the late-nineteenth century in Atlantic hurricane

frequency is nominally negative—though not statistically significant.” The two researchers from NOAA’s Geophysical Fluid Dynamics Laboratory say their results “do not support the hypothesis that the warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase.”

References

- Boose, E.R., Chamberlin, K.E., and Foster, D.R. 2001. Landscape and regional impacts of hurricanes in New England. *Ecological Monographs* **71**: 27–48.
- Chenoweth, M. and Divine, D. 2008. A document-based 318-year record of tropical cyclones in the Lesser Antilles, 1690–2007. *Geochemistry, Geophysics, Geosystems* **9**: 10.1029/2008GC002066.
- Chenoweth, M. and Divine, D. 2012. Tropical cyclones in the Lesser Antilles: descriptive statistics and historical variability in cyclone energy, 1638–2009. *Climatic Change* **113**: 583–598.
- Elsner, J.B. 2007. Tempests in time. *Nature* **447**: 647–649.
- Elsner, J.B. 2008. Hurricanes and climate change. *Bulletin of the American Meteorological Society* **89**: 677–679.
- Elsner, J.B., Liu, K.-B., and Kocher, B. 2000. Spatial variations in major U.S. hurricane activity: statistics and a physical mechanism. *Journal of Climate* **13**: 2293–2305.
- Elsner, J.B., Xufeng, N., and Jagger, T.H. 2004. Detecting shifts in hurricane rates using a Markov Chain Monte Carlo approach. *Journal of Climate* **17**: 2652–2666.
- Emanuel, K., Sundarajan, R., and Williams, J. 2008. Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bulletin of the American Meteorological Society* **89**: 347–367.
- Knutson, T.R., Siutis, J.J., Garner, S.T., Vecchi, G.A., and Held, I.M. 2008. Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience* 10.1038/ngeo202.
- Landsea, C.W., Pielke Jr., R.A., Mestas-Nunez, A.M., and Knaff, J.A. 1999. Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change* **42**: 89–129.
- Landsea, C.W., Vecchi, G.A., Bengtsson, L., and Knutson, T.R. 2010. Impact of duration thresholds on Atlantic tropical cyclone counts. *Journal of Climate* **23**: 2508–2519.
- Mock, C.J. 2008. Tropical cyclone variations in Louisiana, U.S.A., since the late eighteenth century. *Geochemistry, Geophysics, Geosystems* **9**: 10.1029/2007GC001846.

Observations: Extreme Weather

Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Kilbourne, K.H., and Quinn, T.M. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* **447**: 698–702.

Smith, T.M. and Reynolds, R.W. 2004. Improved extended reconstruction of SST (1854–1997). *Journal of Climate* **17**: 2466–2477.

Vecchi, G.A. and Knutson, T.R. 2008. On estimates of historical North Atlantic tropical cyclone activity. *Journal of Climate* **21**: 3580–3600.

Vecchi, G.A. and Knutson, T.R. 2011. Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878–1965) using ship track density. *Journal of Climate* **24**: 1736–1746.

Vermette, S. 2007. Storms of tropical origin: a climatology for New York State, USA (1851–2005). *Natural Hazards* **42**: 91–103.

Wang, C. and Lee, S.-K. 2008. Global warming and United States landfalling hurricanes. *Geophysical Research Letters* **35**: 10.1029/2007GL032396.

7.8.1.1.3 The Past Few Millennia

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? Several studies have examined thousand-year reconstructions of the region’s intense hurricane activity.

Liu and Fearn (1993) analyzed sediment cores retrieved from the center of Lake Shelby in Alabama (USA) to determine the history of intense (Category 4 and 5) hurricane activity over the past 3,500 years. Over the period of their study, “major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years.” The researchers report the last of these hurricane strikes occurred about 700 years ago. It would therefore appear twentieth century global warming has not accelerated the occurrence of such severe storm activity.

Seven years later, Liu and Fern (2000) studied 16 sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico over the past 7,000 years. Twelve major hurricanes of Category 4 or 5 intensity were found to have struck the Western Lake region during this period. Eleven of the 12 events occurred during a 2,400-year period between 1,000 and 3,400 years ago. Only one major hurricane strike was recorded

between 0 and 1,000 years ago, and no major hurricane strikes were recorded between 3,400 and 7,000 years ago.

The two researchers say a probable explanation for the “remarkable increase in hurricane frequency and intensity” that affected the Florida Panhandle and Gulf Coast after 1,400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift south and the Bermuda High southwest of their earlier Holocene positions, such as would be expected with global cooling. They note, “paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime.”

Donnelly and Woodruff (2007) state “it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones,” citing the studies of Emanuel (2005) and Webster *et al.* (2005). Al Gore expressed a similar view in his 21 March 2007 testimony to the U.S. Senate’s Environment & Public Works Committee. Cognizant of the need to consider a longer record of the frequency of occurrence of intense hurricanes than that used by Emanuel and Webster *et al.*, Donnelly and Woodruff developed “a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls.”

The two researchers from the Woods Hole Oceanographic Institution detected three major intervals of intense hurricane strikes: one between 5,400 and 3,600 calendar years before present (yr BP, where “present” is AD 1950), one between 2,500 and 1,000 yr BP, and one after 250 yr BP. They also report coral-based sea surface temperature (SST) data from Puerto Rico “indicate that mean annual Little Ice Age (250–135 yr BP or AD 1700–1815) SSTs were 2–3°C cooler than they are now,” and they state “an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766–1780 was one of the most active intervals in the period between 1500 and 1800 (Garcia-Herrera *et al.*, 2005), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation (Gray *et al.*, 2004).”

Donnelly and Woodruff conclude “the

information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia.” The two researchers write, “studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al.*, 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development.”

Wallace *et al.* (2010) collected a total of 37 sediment cores along eight transects within Laguna Madre, an elongated water body located behind the narrow low-elevation barrier that is Texas, USA’s South Padre Island, constructing a detailed history of intense hurricane strikes from 5,300 to 900 years before present (BP). They report “there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval,” i.e., 5,300–900 yr BP, “implying no direct link between changing climate conditions and annual hurricane impact probability.” In addition, they say “there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time.”

In discussing their findings, as well as the similar results obtained by others for Western Lake, Florida, and Lake Shelby, Alabama, the two Rice University (Houston, Texas, USA) researchers say current rates of intense hurricane impacts “do not seem unprecedented when compared to intense strikes over the past 5000 years,” and “similar probabilities in high-intensity hurricane strikes for the eastern and western Gulf of Mexico do not show any clear-cut out-of-phase relationship that would enlighten us as to climate controls on storm pathways.”

Similarly noting “the brief observational record is inadequate for characterizing natural variability in hurricane activity occurring on longer than multi-decadal timescales,” Lane *et al.* (2011) sought a means of characterizing hurricane activity prior to the period of modern measurement and historical record-keeping, because “the manner in which tropical cyclone activity and climate interact has critical implications for society and is not well understood.” They developed a 4,500-year record of intense hurricane-induced storm surges based on data obtained from “a nearly circular, 200-m-diameter cover-collapse sinkhole (Mullet Pond: 29°55.520’N, 84°20.275’W) that is located on Bald Point near

Apalachee Bay, Florida, USA,” where “recent deposition of sand layers in the upper sediments of the pond was found to be contemporaneous with significant, historic storm surges at the site modeled using SLOSH and the Best Track, post-1851 AD dataset”; “paleohurricane deposits were identified by sand content and dated using radiocarbon-based age models”; and “marine-indicative foraminifera, some originating at least 5 km offshore, were present in several modern and ancient storm deposits.”

The four researchers’ reconstructed record of intense hurricanes revealed the frequency of these “high-magnitude” events “peaked near 6 storms per century between 2800 and 2300 years ago.” The record suggests intense hurricanes were “relatively rare” with “about 0–3 storms per century occurring between 1900 and 1600 years ago,” after which these super-storms exhibited a marked decline, which “began around 600 years ago” and has persisted through the present with “below average frequency over the last 150 years when compared to the preceding five millennia.”

Over the past century and a half of increasing fossil fuel utilization and atmospheric CO₂ buildup, the frequency of the most intense category of hurricanes in the Northeastern Gulf of Mexico has been lower than it was over the prior five millennia, which speaks volumes about the claim that continued anthropogenic CO₂ emissions will lead to more frequent super cyclones and hurricanes.

References

- Bove, M.C., Elsner, J.B., Landsea, C.W., Niu, X.F., and O’Brien, J.J. 1998. Effect of El Niño on US landfalling hurricanes, revisited. *Bulletin of the American Meteorological Society* **79**: 2477–2482.
- Donnelly, J.P. and Woodruff, J.D. 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African Monsoon. *Nature* **447**: 465–468.
- Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.
- Garcia-Herrera, R., Gimeno, L., Ribera, P., and Hernandez, E. 2005. New records of Atlantic hurricanes from Spanish documentary sources. *Journal of Geophysical Research* **110**: 1–7.
- Gray, S.T., Graumlich, L.J., Betancourt, J.L., and Pederson, G.T. 2004. A tree-ring-based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical Research Letters* **31**: 1–4.
- Gray, W.M. 1984. Atlantic seasonal hurricane frequency.

Observations: Extreme Weather

Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Monthly Weather Review* **112**: 1649–1668.

Lane, P., Donnelly, J.P., Woodruff, J.D., and Hawkes, A.D. 2011. A decadal-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. *Marine Geology* **287**: 14–30.

Liu, K.-b. and Fearn, M.L. 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* **21**: 793–796.

Liu, K.-b. and Fearn, M.L. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* **54**: 238–245.

Wallace, D.J. and Anderson, J.B. 2010. Evidence of similar probability of intense hurricane strikes for the Gulf of Mexico over the late Holocene. *Geology* **38**: 511–514.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846.

7.8.1.2 Intensity

Setting the stage for a discussion of the effects of CO₂-induced global warming on Atlantic Ocean hurricane intensity, Free *et al.* (2004) note “increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al.*, 1998; Knutson *et al.*, 1998),” but “because the predicted increase in intensity for doubled CO₂ is only 5%–20%, changes over the past 50 years would likely be less than 2%—too small to be detected easily.” In addition, they say “studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al.*, 1996; Henderson-Sellers *et al.*, 1998; Solow and Moore, 2002).” Several studies have found yearly hurricane numbers to decline as temperatures rise (see Section 7.10.1.1).

Free *et al.* look not for increases in hurricane intensity, but for increases in potential hurricane intensity, because, as they describe it, “changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity.” They analyzed radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans and compared their results with those of Bister and Emanuel (2002) at

grid points near the selected stations. Their results “show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995.” In addition, between 1975 and 1980, “while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone.”

In the following year, some important new studies prompted a reissuing of the claim that warming enhances tropical cyclone intensity (Emanuel, 2005; Webster *et al.*, 2005), but a new review of the subject once again cast doubt on this contention. Pielke *et al.* (2005) begin their discussion by noting “globally there has been no increase in tropical cyclone frequency over at least the past several decades,” citing the studies of Lander and Guard (1998), Elsner and Kocher (2000), and Webster *et al.* (2005). Furthermore, they note research on possible future changes in hurricane frequency due to global warming has produced studies that “give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to base any projections about the future.”

With respect to hurricane intensity, Pielke *et al.* note Emanuel (2005) claimed to have found “a very substantial upward trend in power dissipation (i.e., the sum over the life-time of the storm of the maximum wind speed cubed) in the North Atlantic and western North Pacific,” but “other studies that have addressed tropical cyclone intensity variations (Landsea *et al.*, 1999; Chan and Liu, 2004) show no significant secular trends during the decades of reliable records.” In addition, Pielke *et al.* point out early theoretical work by Emanuel (1987) “suggested an increase of about 10% in wind speed for a 2°C increase in tropical sea surface temperature,” but more recent work by Knutson and Tuleya (2004) points to only a 5% increase in hurricane windspeeds by 2080, and Michaels *et al.* (2005) conclude even this projection is likely twice as great as it should be.

Perhaps of greatest significance to the prediction of future hurricanes and the destruction they may cause is the nature and degree of human occupation of exposed coastal areas. By 2050, for example, Pielke *et al.* report “for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between \$22 and \$60 of increase in damage due to population growth and wealth,” citing the findings of Pielke *et al.* (2000). They state, without equivocation, “the

primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms.”

Pielke *et al.* note many continue to claim a significant hurricane–global warming connection for the purpose of advocating anthropogenic CO₂ emissions reductions that “simply will not be effective with respect to addressing future hurricane impacts,” additionally noting “there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997).”

In a subsequent analysis of Emanuel’s (2005) and Webster *et al.*’s (2005) claims that “rising sea surface temperatures (SSTs) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas concentrations,” Michaels *et al.* (2006) used weekly averaged 1° latitude by 1° longitude SST data together with hurricane track data of the National Hurricane Center, which provide hurricane-center locations (latitude and longitude in tenths of a degree) and maximum one-minute surface wind speeds (both at six-hour intervals) for all tropical storms and hurricanes in the Atlantic basin that occurred between 1982 (when the SST data set begins) through 2005. Plotting maximum cyclone wind speed against the maximum SST that occurred prior to (or concurrent with) the maximum wind speed of each of the 270 Atlantic tropical cyclones of their study period, they found for each 1°C increase in SST between 21.5°C and 28.25°C, the maximum wind speed attained by Atlantic basin cyclones rises, in the mean, by 2.8 m/s, and thereafter, as SSTs rise still further, the first Category-3-or-greater storms begin to appear. However, they report, “there is no significant relationship between SST and maximum winds at SST exceeding 28.25°C.”

Michaels *et al.* conclude, “while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones.” The comparison of SSTs actually encountered by individual storms performed by Michaels *et al.*—as opposed to the comparisons of Emanuel (2005) and Webster *et al.* (2005), which utilized basin-wide averaged monthly or seasonal SSTs—refutes the idea that anthropogenic activity has detectably influenced the severity of Atlantic

basin hurricanes over the past quarter-century.

Balling and Cervený (2006) examined temporal patterns in the frequency of intense tropical cyclones (TCs), the rates of rapid intensification of TCs, and the average rate of intensification of hurricanes in the North Atlantic Basin, including the tropical and subtropical North Atlantic, Caribbean Sea, and Gulf of Mexico, where they say there was “a highly statistically significant warming of 0.12°C decade⁻¹ over the period 1970–2003 ... based on linear regression analysis and confirmed by a variety of other popular trend identification techniques.” They found “no increase in a variety of TC intensification indices,” and “TC intensification and/or hurricane intensification rates ... are not explained by current month or antecedent sea surface temperatures (despite observed surface warming over the study period).” Thus they conclude, “while some researchers have hypothesized that increases in long-term sea surface temperature may lead to marked increases in TC storm intensity, our findings demonstrate that various indicators of TC intensification show no significant trend over the recent three decades.”

Klotzbach and Gray (2006) note still other papers question the validity of the findings of Emanuel (2005) and Webster *et al.* (2005) “due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea, 2005).” “While major hurricane activity in the Atlantic has shown a large increase since 1995,” they note, “global tropical-cyclone activity, as measured by the accumulated cyclone energy index, has decreased slightly during the past 16 years (Klotzbach, 2006).” They “attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal mode and strength of the Atlantic Ocean thermohaline circulation.” They note, “historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25–30 years (typical period ~50–60 years; Gray *et al.*, 1997; Latif *et al.*, 2004),” and “since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15–20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity,” demonstrating the science of this subject is far from settled.

Vecchi and Soden (2007a) explored twenty-first

Observations: Extreme Weather

century projected changes in vertical wind shear (VS) over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions scenario A1B (atmospheric CO₂ stabilization at 720 ppm by 2100) of the Intergovernmental Panel on Climate Change's *Fourth Assessment Report*, where VS is defined as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa, and where changes are computed between the two 20-year periods 2001–2020 and 2081–2100. The 18-model mean result indicated a prominent increase in VS over the tropical Atlantic and East Pacific (10°N–25°N). Noting “the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity,” the two researchers state the projected changes “would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century.” They further note, “in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America.” Consequently, and in addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes (Donnelly and Woodruff, 2007; Nyberg *et al.*, 2007), there is now considerable up-to-date model-based evidence for that conclusion.

In a second, closely related paper, Vecchi and Soden (2007b) used climate models and observational reconstructions “to explore the relationship between changes in sea surface temperature and tropical cyclone ‘potential intensity’—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development.” They found “changes in local sea surface temperature are inadequate for characterizing even the sign of changes in potential intensity.” Instead, they report “long-term changes in potential intensity are closely related to the regional structure of warming,” such that “regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa.”

Using this relationship to reconstruct changes in potential intensity over the twentieth century, based on observational reconstructions of sea surface temperature, they found “even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably

peaked in the 1930s and 1950s,” noting “recent values are near the historical average.” The two scientists concluded the response of tropical cyclone activity to natural climate variations “may be larger than the response to the more uniform patterns of greenhouse-gas-induced warming.”

Latif *et al.* (2007) analyzed the 1851–2005 history of Accumulated Cyclone Energy or ACE Index for the Atlantic basin. This parameter “takes into account the number, strength and duration of all tropical storms in a season.” They then “analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870–2003.”

With respect to the first part of their study, they report “the ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but no sustained long-term trend.” With respect to the second part of their study, they report “a clear warming trend is seen in the tropical North Atlantic sea surface temperature,” but this warming trend “does not seem to influence the tropical storm activity.”

This state of affairs seemed puzzling at first, because a warming of the tropical North Atlantic is known to reduce vertical wind shear there and thus promote the development of tropical storms. However, Latif *et al.*'s modeling work revealed a warming of the tropical Pacific enhances the vertical wind shear over the Atlantic, as does a warming of the tropical Indian Ocean. Consequently, they learned “the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic,” and “apparently, the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity [has] remained rather stable and mostly within the range of the natural multidecadal variability.”

A striking exception occurred in 2005 when, the researchers report, “the tropical North Atlantic warmed more rapidly than the Indo-Pacific,” which reduced vertical wind shear over the North Atlantic, producing the most intense Atlantic hurricane season of the historical record. By contrast, they note the summer and fall of 2006 were “characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the

tropical North Atlantic and the tropical Indian and Pacific Oceans,” and “this explains the weak tropical storm activity [of that year].”

Clearly, the temperature/hurricane connection is nowhere near as “one-dimensional” as Al Gore and others make it out to be. Warming alone does *not* ensure hurricanes will get stronger. Instead, as Latif *et al.* describe it, “the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region.” They note “changes in the meridional overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered” and “changes in ENSO statistics in the tropical Pacific may become important.”

Scileppi and Donnelly (2007) note “when a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats,” and long-term records of hurricane activity are thus formed “as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers.” Based on this knowledge, they refined and lengthened the hurricane record of the New York City area by calibrating the sedimentary record of surrounding backbarrier environments to documented hurricanes—including those of 1893, 1821, 1788, and 1693—and extracting several thousand additional years of hurricane history from the sedimentary archive.

The two researchers determined “alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales.” They point out “several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550–1850 AD) when sea surface temperatures were generally colder than present,” and “no major hurricanes have impacted this area since 1893,” when Earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

Noting Emanuel (2005) and Webster *et al.* (2005) had produced analyses suggesting “cooler climate conditions in the past may have resulted in fewer strong hurricanes,” whereas their own findings suggest just the opposite, Scileppi and Donnelly conclude “other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower sea surface temperatures” prior to the development of the

Current Warm Period.

Briggs (2008) developed Bayesian statistical models for the number of tropical cyclones, the rate at which these cyclones became hurricanes, and the rate at which the hurricanes became Category 4+ storms in the North Atlantic, based on data from 1966 to 2006. He concluded there is “no evidence that the distributional mean of individual storm intensity, measured by storm days, track length, or individual storm power dissipation index, has changed (increased or decreased) through time.”

Chylek and Lesins (2008) applied “simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity, and other features of interest.” Noting “the last minimum in hurricane activity occurred around 1980,” the two researchers compared the two 28-year-long periods on either side of this date and found “a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification.” Hence, they conclude “if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured.”

Vecchi *et al.* (2008) note “a key question in the study of near-term climate change is whether there is a causal connection between warming tropical sea surface temperatures (SSTs) and Atlantic hurricane activity.” They explain in more detail the two schools of thought on this topic: one posits the intensity of Atlantic Basin hurricanes is directly related to the absolute SST of the basin’s main development region, which would be expected to rise in response to global warming, and the other posits Atlantic hurricane intensity is directly related to the SST of the Atlantic basin’s main development region relative to the SSTs of the other tropical ocean basins, which could either rise or fall to a modest degree in response to global warming—and possibly even cycle between the two modes.

Vecchi *et al.* proceeded to plot Atlantic hurricane power dissipation index (PDI) anomalies calculated from both the absolute SST values of the Atlantic Basin and the relative SST values derived from all tropical ocean basins as a function of time, extending them throughout most of the current century based on projections of the two parameters obtained from 24 climate models. They compared the results they obtained for the period 1946–2007 with the measured PDI anomalies. They found the relative SST “is as well correlated with Atlantic hurricane activity as the

absolute SST.” They also report the “relative SST does not experience a substantial trend in 21st-century projections,” and therefore, “a future where relative SST controls Atlantic hurricane activity is a future similar to the recent past, with periods of higher and lower hurricane activity relative to present-day conditions due to natural climate variability, but with little long-term trend.”

Vecchi *et al.* say their work “suggests that we are presently at an impasse,” and “many years of data will be required to reject one hypothesis in favor of the other,” as the projections derived from the absolute and relative SST parameters “do not diverge completely until the mid-2020s.” If the absolute SST ultimately proves to be the proper forcing factor, projections of more-intense Atlantic hurricanes would have some validity. But if the relative SST proves to be the controlling factor, the researchers note, “an attribution of the recent increase in hurricane activity to human activities is not appropriate, because the recent changes in relative SST in the Atlantic are not yet distinct from natural climate variability.”

Climate modelers are not quite ready to throw in the towel, as evidenced from a recent report from Bender *et al.* (2010). They “explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy by using an operational hurricane-prediction model that produces a realistic distribution of intense hurricane activity for present-day conditions,” working with 18 models from the World Climate Research Program’s Coupled Model Intercomparison Project 3 and employing the Intergovernmental Panel on Climate Change’s A1B emissions scenario.

They found “an increase in the number of the most intense storms for the warmer climate compared with the control climate.” Bender *et al.* predicted for “category 4 and 5 hurricanes with maximum winds greater than 60 m/s, the total number increased sharply from 24 to 46,” and “hurricanes with winds greater than 65 m/s increased from 6 to 21.” However, they also report there were reductions in the total number of hurricanes of all categories, which seems to contradict their own findings.

The researchers comment on the wide range of variability in the model predictions. They note, for example, an increase in hurricane-caused “damage potential” of +30% was projected for the 18-model ensemble, but a range of -50% to +70% was found for four models for which they did more detailed work. This extreme variability reduces confidence in their mean result.

Bender *et al.*’s findings clearly contradict the supposed link between the occurrence of strong hurricanes of the recent past with what many have claimed was unnatural and unprecedented CO₂-induced global warming. Quite to the contrary, and although the new model results suggest “a significant anthropogenic increase in the frequency of very intense Atlantic hurricanes may emerge from the background climate variability,” the researchers say this development likely would not occur until “the latter half of the 21st century.”

As is nearly always the case in climate modeling work, Kerr (2010) reports, in a commentary on Bender *et al.*’s study, that the researchers “are looking for yet more computer power and higher resolution to boost the realism of simulations.” If those improvements are realized, and “if the models continue to converge as realism increases,” Kerr writes, “the monster storms that seemed to be already upon us would be removed to decades hence.”

But who really knows, when one is working with decidedly imperfect models of a complex planetary climate and weather system? As Kerr reports, even the researchers themselves “caution” their findings are still “far from the last word” on the subject.

Following up on an earlier paper (Chenoweth and Divine, 2008) in which they “presented a 318-year record of tropical cyclone activity in the Lesser Antilles and determined that there [was] no statistically significant change in the frequency of tropical cyclones (tropical storms and hurricanes) as well as tropical depressions over the entire length of the record,” Chenoweth and Divine (2012) conducted a new analysis in which they examined the records employed in their earlier paper in more detail. They determined “the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian.”

Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends. Chenoweth and Divine report their record of tropical cyclone activity “reveals no trends in LACE in the best-sampled regions for the past 320 years,” and “even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or

LACE.” In addition, they note LACE along the 61.5°W meridian is “highly correlated” with Atlantic-Basin-wide ACE, suggesting their findings may extend beyond their region of study.

References

- Balling Jr., R.C. and Cervený, R.S. 2006. Analysis of tropical cyclone intensification trends and variability in the North Atlantic Basin over the period 1970–2003. *Meteorological and Atmospheric Physics* **93**: 45–51.
- Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T., and Held, I.M. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* **327**: 454–458.
- Bister, M. and Emanuel, K. 2002. Low frequency variability of tropical cyclone potential intensity. 1. Interannual to interdecadal variability. *Journal of Geophysical Research* **107**: 10.1029/2001JD000776.
- Briggs, W.M. 2008. On the changes in the number and intensity of North Atlantic tropical cyclones. *Journal of Climate* **21**: 1387–1402.
- Chan, J.C.L. and Liu, S.L. 2004. Global warming and western North Pacific typhoon activity from an observational perspective. *Journal of Climate* **17**: 4590–4602.
- Chenoweth, M. and Divine, D. 2008. A document-based 318-year tropical cyclone record for the Lesser Antilles, 1690–2007. *Geochemistry, Geophysics Geosystems* **9**: 10.1029/2008GC002066.
- Chenoweth, M. and Divine, D. 2012. Tropical cyclones in the Lesser Antilles: descriptive statistics and historical variability in cyclone energy, 1638–2009. *Climatic Change* **113**: 583–598.
- Chylek, P. and Lesins, G. 2008. Multidecadal variability of Atlantic hurricane activity: 1851–2007. *Journal of Geophysical Research* **113**: 10.1029/2008JD010036.
- Donnelly, J.P. and Woodruff, J.D. 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African Monsoon. *Nature* **447**: 465–468.
- Elsner, J.B. and Kocher, B. 2000. Global tropical cyclone activity: A link to the North Atlantic Oscillation. *Geophysical Research Letters* **27**: 129–132.
- Emanuel, K.A. 1986. An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *Journal of the Atmospheric Sciences* **43**: 585–604.
- Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. *Nature* **326**: 483–485.
- Emanuel, K.A. 1995. Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *Journal of the Atmospheric Sciences* **52**: 3969–3976.
- Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.
- Free, M., Bister, M., and Emanuel, K. 2004. Potential intensity of tropical cyclones: comparison of results from radiosonde and reanalysis data. *Journal of Climate* **17**: 1722–1727.
- Gray, W.M., Sheaffer, J.D., and Landsea, C.W. 1997. Climate trends associated with multi-decadal variability of Atlantic hurricane activity. In: Diaz, H.F. and Pulwarty, R.S. (Eds.) *Hurricanes: Climate and Socioeconomic Impacts*, Springer-Verlag, pp. 15–52.
- Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., and McGuffie, K. 1998. Tropical cyclones and global climate change: a post-IPCC assessment. *Bulletin of the American Meteorological Society* **79**: 19–38.
- Kerr, R.A. 2010. Models foresee more-intense hurricanes in the greenhouse. *Science* **327**: 399.
- Klotzbach, P.J. 2006. Trends in global tropical cyclone activity over the past 20 years (1986–2005). *Geophysical Research Letters* **33**: 10.1029/2006GL025881.
- Klotzbach, P.J. and Gray, W.M. 2006. Causes of the unusually destructive 2004 Atlantic basin hurricane season. *Bulletin of the American Meteorological Society* **87**: 1325–1333.
- Knutson, T.R. and Tuleya, R.E. 2004. Impact of CO₂-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *Journal of Climate* **17**: 3477–3495.
- Knutson, T., Tuleya, R., and Kurihara, Y. 1998. Simulated increase of hurricane intensities in a CO₂-warmed climate. *Science* **279**: 1018–1020.
- Lander, M.A. and Guard, C.P. 1998. A look at global tropical cyclone activity during 1995: contrasting high Atlantic activity with low activity in other basins. *Monthly Weather Review* **126**: 1163–1173.
- Landsea, C.W. 2005. Hurricanes and global warming. *Nature* **438**: E11–13, doi:10.1038/nature04477.
- Landsea, C., Nicholls, N., Gray, W., and Avila, L. 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters* **23**: 1697–1700.
- Landsea, C.W., Pielke Jr., R.A., Mestas-Nunez, A.M., and

Observations: Extreme Weather

- Knaff, J.A. 1999. Atlantic basin hurricanes: indices of climatic changes. *Climatic Change* **42**: 89–129.
- Latif, M., Keenlyside, N., and Bader, J. 2007. Tropical sea surface temperature, vertical wind shear, and hurricane development. *Geophysical Research Letters* **34**: 10.1029/2006GL027969.
- Latif, M., Roeckner, E., Botzet, M., Esch, M., Haak, H., Hagemann, S., Jungclaus, J., Legutke, S., Marsland, S., Mikolajewicz, U., and Mitchell, J. 2004. Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature. *Journal of Climate* **17**: 1605–1614.
- Michaels, P.J., Knappenberger, P.C., and Davis, R.E. 2006. Sea-surface temperatures and tropical cyclones in the Atlantic basin. *Geophysical Research Letters* **33**: 10.1029/2006GL025757.
- Michaels, P.J., Knappenberger, P.C., and Landsea, C.W. 2005. Comments on “Impacts of CO₂-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective scheme.” *Journal of Climate* **18**: 5179–5182.
- Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., Kilbourne, K.H., and Quinn, T.M. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* **447**: 698–701.
- Pielke Jr., R.A., Landsea, C., Mayfield, M., Laver, J., and Pasch, R. 2005. Hurricanes and global warming. *Bulletin of the American Meteorological Society* **86**: 1571–1575.
- Pielke Jr., R.A. and Pielke Sr., R.A. 1997. *Hurricanes: Their Nature and Impacts on Society*. John Wiley and Sons.
- Pielke Jr., R.A., Pielke, Sr., R.A., Klein, R., and Sarewitz, D. 2000. Turning the big knob: Energy policy as a means to reduce weather impacts. *Energy and Environment* **11**: 255–276.
- Scileppi, E. and Donnelly, J.P. 2007. Sedimentary evidence of hurricane strikes in western Long Island, New York. *Geochemistry, Geophysics, Geosystems* **8**: 10.1029/2006GC001463.
- Solow, A.R. and Moore, L.J. 2002. Testing for trend in North Atlantic hurricane activity, 1900–98. *Journal of Climate* **15**: 3111–3114.
- Vecchi, G.A. and Soden, B.J. 2007a. Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters* **34**: 10.1029/2006GL028905.
- Vecchi, G.A. and Soden, B.J. 2007b. Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature* **450**: 1066–1070.
- Vecchi, G.A., Swanson, K.L., and Soden, B.J. 2008. Whither hurricane activity? *Science* **322**: 687–689.
- Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R. 2005. Changes in tropical cyclone number, duration and intensity in a warming environment. *Science* **309**: 1844–1846.

7.8.1.3 El Niño Effect

How do Atlantic basin hurricanes respond to increases in temperature? In exploring this question within the context of the warming that occurs in going from cooler La Niña conditions to warmer El Niño conditions, Wilson (1999) analyzed data from the last half of the twentieth century, finding the probability of having three or more intense hurricanes was only 14% during a (relatively) warm El Niño year, but fully 53% during a (relatively) cool La Niña year. Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone the average ranged from 1.7 per La Niña season to 0.5 per El Niño season, a frequency-of-occurrence decline of fully 70% in going from cooler La Niña conditions to warmer El Niño conditions. Elsner *et al.* (2001), who also worked with data from the entire past century, also found “the probability of a U.S. hurricane increases” when there are below-normal sea surface temperatures in the equatorial Pacific.

Lyons (2004) conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three groupings: the 10 highest storm and hurricane landfall years, the nine lowest such years, and all other years. These groupings revealed, in Lyons’ words, “La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years,” and “El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years.” In addition, “La Niña (El Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years.”

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. They first determined 22

years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. They compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a 10-year study carried out on the other side of the Atlantic, Brichetti *et al.* (2000) determined, contrary to their own expectation, that survival rates for a Mediterranean water bird (Cory's Shearwater) were greater during warmer El Niño years than during cooler La Niña years.

Landsea *et al.* (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991–1994) that had exhibited the lowest such activity since the keeping of reliable records began. They determined the most important factor behind this transition was what they called the “dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions.”

In a twentieth century changepoint analysis of time series of major North Atlantic and U.S. annual hurricane counts, which Elsner *et al.* (2004) say “quantitatively identifies temporal shifts in the mean value of the observations,” the authors found “El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida.”

As for why North Atlantic hurricane activity is suppressed under warmer El Niño conditions, Donnelly and Woodruff (2007) opined it was “due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development.” Such a conclusion is supported by the results of two analyses conducted by Klotzbach. Klotzbach (2011a) examined Caribbean tropical cyclone activity over the period 1900–2008, looking for impacts from the El Niño–Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). He found “the probability of one or more hurricanes and major hurricanes tracking through the Caribbean increases dramatically from 39% and 26% in the 10 warmest ENSO years to 92% and 63% in the 10 coldest ENSO

years, respectively,” in harmony with the similar findings of Tartaglione *et al.* (2003), who additionally demonstrated this cooling-induced response was likely due to “reductions in vertical wind shear and increases in low-level vorticity” in La Niña conditions. This connection also was demonstrated by Klotzbach, who determined “for the 10 warmest events since 1948, the average 200–850-mb zonal wind shear in the Caribbean was 7 m/s compared with only 3 m/s in the 10 coldest events since 1948.”

The Colorado State University researcher also determined “the impacts of ENSO are reduced slightly when the AMO is positive,” and he found “a negative AMO phase and El Niño combine to provide large-scale climate features that are especially hostile for tropical cyclones.” He reports, for example, “29 hurricanes tracked into the Caribbean in the 10 strongest La Niña years in a positive AMO period compared with only two hurricanes tracking through the Caribbean in the 10 strongest El Niño years in a negative Atlantic multidecadal oscillation period.”

Similar findings were reported in Klotzbach's second paper (2011b), which expanded his analysis beyond the Caribbean and throughout the Atlantic basin.

In addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes, there exists model-based evidence for the same conclusion. Vecchi and Soden (2007), for example, explored “21st Century projected changes in VS [vertical wind shear] over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions Scenario A1B (atmospheric CO₂ stabilization at 720 ppm by year 2100) for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4),” where VS was defined as “the magnitude of the vector difference between monthly-mean winds at 850 hPa and 200 hPa,” and where “changes are computed between two 20-year periods: 2001–2020 and 2081–2100.”

The analysis revealed the 18-model ensemble-mean projected change in VS over the twenty-first century is “a prominent increase in VS over the tropical Atlantic and East Pacific (10°N–25°N).” Noting “the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity,” they state the projected changes “would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific

hurricane activity during the 21st Century,” and “in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America.”

References

Brichetti, P., Foschi, U.F., and Boano, G. 2000. Does El Niño affect survival rate of Mediterranean populations of Cory’s Shearwater? *Waterbirds* **23**: 147–154.

Donnelly, J.P. and Woodruff, J.D. 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African Monsoon. *Nature* **447**: 465–468.

Elsner, J.B. Bossak, B.H., and Niu, X.F. 2001. Secular changes to the ENSO-U.S. hurricane relationship. *Geophysical Research Letters* **28**: 4123–4126.

Elsner, J.B., Niu, X., and Jagger, T.H. 2004. Detecting shifts in hurricane rates using a Markov Chain Monte Carlo approach. *Journal of Climate* **17**: 2652–2666.

Klotzbach, P.J. 2011a. The influence of El Niño-Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean tropical cyclone activity. *Journal of Climate* **24**: 721–731.

Klotzbach, P.J. 2011b. El Niño-Southern Oscillation’s impact on Atlantic basin hurricanes and U.S. landfalls. *Journal of Climate* **24**: 1252–1263.

Landsea, C.W., Bell, G.D., Gray, W.M., and Goldenberg, S.B. 1998. The extremely active 1995 Atlantic hurricane season: environmental conditions and verification of seasonal forecasts. *Monthly Weather Review* **126**: 1174–1193.

Lyons, S.W. 2004. U.S. tropical cyclone landfall variability: 1950–2002. *Weather and Forecasting* **19**: 473–480.

Muller, R.A. and Stone, G.W. 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast U.S. coast. *Journal of Coastal Research* **17**: 949–956.

Pielke Jr., R.A. and Landsea, C.N. 1999. La Niña, El Niño, and Atlantic hurricane damages in the United States. *Bulletin of the American Meteorological Society* **80**: 2027–2033.

Tartaglione, C.A., Smith, S.R., and O’Brien, J.J. 2003. ENSO impact on hurricane landfall probabilities for the Caribbean. *Journal of Climate* **16**: 2925–2931.

Vecchi, G.A. and Soden, B.J. 2007. Increased tropical Atlantic wind shear in model projections of global

warming. *Geophysical Research Letters* **34**: 10.1029/2006GL028905.

Wilson, R.M. 1999. Statistical aspects of major (intense) hurricanes in the Atlantic basin during the past 49 hurricane seasons (1950–1998): Implications for the current season. *Geophysical Research Letters* **26**: 2957–2960.

7.8.2 Indian Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Indian Ocean.

Hassim and Walsh (2008) analyzed tropical cyclone (TC) best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) for the presence of systematic intensity and duration trends over the cyclone season from 1969–1970 through 2004–2005. Their results indicated “the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones [increased] since 1980.” A contemporaneous study of roughly the same region and time period by Harper *et al.* (2008) yielded a much different result.

Harper *et al.* analyzed several “potential influences on the accuracy of estimating TC intensity over time due to increasing technology, methodology, knowledge and skill” for TCs that occurred off the coast of northwestern Australia, primarily in a band between 5 and 25°S, over the period 1968–1969 to 2000–2001. The four Australian researchers show “a bias towards lower intensities likely exists in earlier (mainly pre-1980) TC central pressure deficit estimates of the order of at least 20% in 1970, reducing to around ten% by 1980 and to five% in 1985.” They report “inferred temporal trends in the estimated intensity from the original data-sets are therefore significantly reduced in the objectively reviewed data-set.” Thus they conclude “there is no prima facie evidence of a potential climate-change induced trend in TC intensity in northwestern Australia over the past 30 years.”

Similar findings were reported two years later by Goebbert and Leslie (2010), who examined interannual TC variability of the northwest Australian (NWAUS) sub-basin of the southeastern Indian

Ocean (0–35°S, 105°–135°E) over the 39-year time period 1970–2008, using the Woodside Petroleum Ltd. reanalysis TC dataset described by Harper *et al.* (2008). The two researchers could find “no significant linear trends in either mean annual TC frequencies or TC days” and “no trend in the number of intense TCs for the NWAUS sub-basin.” They note “none of the 13 NWAUS TC metrics exhibited statistically significant linear trends.” They conclude, “known climate indices—such as Niño-3.4, Niño-4, SOI, NOI, PDO, NAO, and others—generally were found not to be significantly correlated to the variability of TC frequency or TC days in the NWAUS region.”

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed “the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs.” Regarding the southeast Indian Ocean, for example, Hall determined “the overall number of depressions and tropical cyclones was below the long-term mean.” Further east, he found broad-scale convection was near or slightly above normal, but “the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average,” which represented “a continuation of the trend of the previous few seasons.” Hall’s work, like that of Harper *et al.* (2008) and Goebbert and Leslie (2010), suggests a likely decline in both the intensity and frequency of Indian-Ocean tropical cyclones if the world warms in the future.

Singh *et al.* (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877–1998. The planet was recovering from the global chill of the Little Ice Age at this time, making it logical to assume their findings would be indicative of changes in hurricane characteristics that might be expected if Earth were to warm by that amount again, which is what the IPCC models project it will do.

On an annual basis, Singh *et al.* report there was a slight decrease in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one fewer hurricane per year at the end of the 122-year record in 1998 than at its start in 1877. In addition, based on data from the Bay of Bengal, they

found tropical cyclone numbers dropped during the months of most severe cyclone formation (November and May) when the El Niño-Southern Oscillation was in a warm phase. In light of these observations, it would appear that if tropical cyclones of the North Indian Ocean were to change at all in response to global warming, their overall frequency and the frequency of the most intense such storms would likely decrease, just the opposite of what climate models typically suggest will occur.

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world and specifically the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report for the period 1891–1997 there was a significant decreasing trend (at the 99% confidence level) in the frequency of cyclones with the designation of “cyclonic storm” and above, and “the maximum decrease was in the last four decades,” citing the work of Srivastava *et al.* (2000). In addition, they note Singh and Khan (1999) also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

Raghavan and Rajesh say “there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change.” However, they continue, “studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones.” Thus they confidently state “the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular media and even in some more serious publications, does not therefore have a sound scientific basis.”

Kumar and Sankar (2010) say “an important concern about the consequences of the global warming scenario is its impact on the frequency, the intensity, and the duration of tropical cyclones,” noting “theoretical and modeling studies indicate that tropical cyclone winds would increase with increasing ocean temperature.” To see to what extent the implications of these theoretical model studies harmonize with what actually occurred throughout the North Indian Ocean over the period 1901–2007, Kumar and Sankar employed “various datasets, such

Observations: Extreme Weather

as the NCEP/NCAR Reanalysis dataset, the ERSST and the tracks of storms and depressions over the north Indian Ocean for different seasons based on the period 1901–2007,” comparing “changes that occurred during the period 1951–2007 and the previous period, 1901–1951.” They also compared the sub-period 1951–1978 (epoch I) with the sub-period 1979–2007 (epoch II).

The two researchers determined “the frequency of storms and severe storms do not show a dramatic rise in spite of a substantial increase in the sea surface temperature in the Bay of Bengal from 1951–2007 compared to 1901–1951.” Also, while noting “the Bay of Bengal has been warming throughout the year during epoch II compared to epoch I,” they report “the number of both storms and severe storms, have decreased largely over the Bay of Bengal.” Such findings, they write, “clearly indicate that warm SST’s alone are not sufficient for the initiation of convective systems over the Arabian Sea and the Bay of Bengal,” noting their results suggest a “decreasing trend in the frequency of storms over the Bay of Bengal, contrary to the popular belief that there will be an increase.”

The authors note “in the current debate on global warming and the change in the number of intense cyclones, initial studies carried out have shown very different results for the northern Indian Ocean,” where, as they describe it, “Webster *et al.* (2005) found that there had been a considerable increase in the number of categories 4 and 5 cyclones with a maximum sustained wind reaching at least 115 knots.” They note, however, Landsea *et al.* (2006) subsequently demonstrated the databases employed by Webster *et al.* “were not sufficiently reliable,” as “cyclones archived as being categories 2 or 3 had been re-analyzed and assigned as categories 4 or 5.” They also note, “Kossin *et al.* (2007) did not note any trend towards an increase in the number of categories 4 and 5 cyclones in the northern Indian Ocean for their period of analysis, which covered from 1983 to 2005.”

Hoarau *et al.* (2012) analyzed intense cyclone activity in the northern Indian Ocean from 1980 to 2009 on the basis of a homogenous reanalysis of satellite imagery. The three French researchers conclude “there has been no trend towards an increase in the number of categories 3–5 cyclones over the last 30 years,” noting “the decade from 1990 to 1999 was by far the most active with 11 intense cyclones while 5 intense cyclones formed in each of the other two decades”; i.e., those that preceded and followed the

1990s. They state there has “not been a regular increase in the number of cyclone ‘landfalls’ over the last three decades (1980–2009).”

References

- Goebbert, K.H. and Leslie, L.M. 2010. Interannual variability of Northwest Australian tropical cyclones. *Journal of Climate* **23**: 4538–4555.
- Hall, J.D. 2004. The South Pacific and southeast Indian Ocean tropical cyclone season 2001–02. *Australian Meteorological Magazine* **53**: 285–304.
- Harper, B.A., Stroud, S.A., McCormack, M., and West, S. 2008. A review of historical tropical cyclone intensity in northwestern Australia and implications for climate change trend analysis. *Australian Meteorological Magazine* **57**: 121–141.
- Hassim, M.E.E. and Walsh, K.J.E. 2008. Tropical cyclone trends in the Australian region. *Geochemistry, Geophysics, Geosystems* **9**: 10.1029/2007GC001804.
- Hoarau, K., Bernard, J., and Chalonge, L. 2012. Intense tropical cyclone activities in the northern Indian Ocean. *International Journal of Climatology* **32**: 1935–1945.
- Kumar, M.R.R. and Sankar, S. 2010. Impact of global warming on cyclonic storms over north Indian Ocean. *Indian Journal of Geo-Marine Science* **39**: 516–520.
- Raghavan, S. and Rajesh, S. 2003. Trends in tropical cyclone impact: a study in Andhra Pradesh, India. *Bulletin of the American Meteorological Society* **84**: 635–644.
- Singh, O.P. and Ali Khan, T.M. 1999. *Changes in the frequencies of cyclonic storms and depressions over the Bay of Bengal and the Arabian Sea*. SMRC Report 2. South Asian Association for Regional Cooperation, Meteorological Research Centre, Agargaon, Dhaka, Bangladesh.
- Singh, O.P., Ali Khan, T.M., and Rahman, S. 2000. Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorology and Atmospheric Physics* **75**: 11–20.
- Singh, O.P., Ali Kahn, T.M., and Rahman, S. 2001. Has the frequency of intense tropical cyclones increased in the North Indian Ocean? *Current Science* **80**: 575–580.
- Srivastava, A.K., Sinha Ray, K.C., and De, U.S. 2000. Trends in the frequency of cyclonic disturbances and their intensification over Indian seas. *Mausam* **51**: 113–118.

7.8.3 Pacific Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Pacific Ocean.

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that originated in or entered the central North Pacific (0–70°N, 140–180°W) over the 32-year period 1966–1997. They found “tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise.” This increase appears to have been due to a step-change that led to the creation of “fewer cyclones during the first half of the record (1966–81) and more during the second half of the record (1982–1997).” Accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity.

Although these findings may appear to support model-based projections that CO₂-induced global warming leads to more frequent and stronger hurricanes, Chu and Clark state the observed increase in tropical cyclone activity cannot be due to CO₂-induced global warming, because, in their words, “global warming is a gradual process” and “it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s.”

A much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark and their relationship to mean global air temperature. The beginnings of such a history were presented by Liu *et al.* (2001), who waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975.

Calibrating the historical data against instrumental observations over the period 1884–1909, they found the trends of the two datasets were significantly correlated ($r = 0.71$), and this observation led them to conclude “the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls.” They conducted a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that “suggests an external forcing mechanism, which remains to be identified.” Also, and importantly, they found “the two periods of most

frequent typhoon strikes in Guangdong (AD 1660–1680, 1850–1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age.”

Hayne and Chappell (2001) studied a series of storm ridges at Curacao Island, deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events affecting that area, with one of their stated reasons for doing so being to test the climate-model-based hypothesis that “global warming leads to an increase of cyclone frequency or intensity.” They found “cyclone frequency was statistically constant over the last 5,000 years,” and they could find “no indication that cyclones have changed in intensity.”

Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S, by geologically dating and topographically surveying landform features left by historic hurricanes and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed several “super-cyclones” with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred during the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of their study. They also report the Great Barrier Reef “experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870.” The twentieth century was totally devoid of such storms, “with only one such event (1899) since European settlement in the mid-nineteenth century.”

Noting “many researchers have suggested that the buildup of greenhouse gases (Watson *et al.*, 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs),” Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data. They explain, “if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades.”

Focusing on the last four decades of the twentieth century, they found a number of parameters related to SST and TC activity in the Western North Pacific (WNP) “have gone through large interannual as well as interdecadal variations,” and “they also show a

Observations: Extreme Weather

slight decreasing trend.” In addition, they write, “no significant correlation was found between the typhoon activity parameters and local SST.” They write, “in other words, an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models.”

Chan and Liu suggest the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere. “In other words,” they state, “the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999),” whereas “in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process.” They conclude, “at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs.”

Free *et al.* (2004) looked not for increases in actual hurricane intensity, but instead for increases in potential hurricane intensity, because “changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity.” They used radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific and Atlantic Oceans and compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They found “no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995.” Between 1975 and 1980, they further report, “while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone.”

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36

years before that. This analysis indicated “the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs.” In the southeast Indian Ocean, for example, “the overall number of depressions and tropical cyclones was below the long-term mean.” Further east he found broad-scale convection was near or slightly above normal, but “the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average,” which represented “a continuation of the trend of the previous few seasons.” Hall writes, “in the eastern Australian region, the four-year period up to 2001–2002 was by far the quietest recorded in the past 41 years.”

Noting Emanuel (2005) and Webster *et al.* (2005) had claimed “tropical cyclone intensity has increased markedly in recent decades” and “tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming,” Ren *et al.* (2006) analyzed tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced torrential precipitation events. They report “significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years.” They also state the downward trends were accompanied by “decreases in the numbers of TCs and typhoons that affected China during the period 1957–2004.” In a conclusion that differs dramatically from the claims of Emanuel (2005) and Webster *et al.* (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al.* say their findings “strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP.”

Wu *et al.* (2006) ran two independent checks on Webster *et al.*’s findings by performing analyses of best track data from the Regional Specialized Meteorological Centre (RSMC) Tokyo (Japan) and from the Hong Kong Observatory (HKO; Hong Kong, China). This work revealed, “in contrast to Webster *et al.*’s findings, there was no increase in western North Pacific category 4–5 typhoon activity,” and “neither RSMC-Tokyo nor HKO best track data suggest an increase in western North Pacific tropical cyclone destructiveness as measured by the potential

destructive index (PDI),” in contrast to the findings of Emanuel (2005).

Wu *et al.* state the RSMC-Tokyo data “show a decrease in the proportion of category 4–5 typhoons from 18% to 8% between the two periods 1977–1989 and 1990–2004,” noting “the result is the same if the analysis is extended to include 2005” and the trend is “statistically significant at the 5% level.” In addition, they report “HKO best track data show a decrease in the proportion of category 4–5 typhoons, from 32% to 16%, between 1975–1989 and 1990–2004,” noting this result too is “statistically significant at the 5% level” and it also “remains unchanged if the end year is extended to 2005.”

Nott *et al.* (2007) developed a 777-year-long annually resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. They found “the period between AD 1600 to 1800”—when the Little Ice Age held sway throughout the world—“had many more intense or hazardous cyclones impacting the site than the post AD 1800 period,” when the planet gradually began to warm. The four researchers point out “the only way to determine the likely future behavior of tropical cyclones is to first understand their history from high resolution records of multi-century length or greater.”

Li *et al.* (2007) analyzed tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949–2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951–2003. They used their empirical findings to infer future tropical cyclone activity in the region based on climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed there were “more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present.” They further found “the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones.”

Based on simulations of future occurrences of these favorable and unfavorable conditions derived

from “a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios,” they then determined “the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it.”

Chan (2007) searched for “possible physical causes responsible for the interannual variations of the activity of intense typhoons in the WNP [Western North Pacific] (here defined as the region 0–40°N, 120–180°E).” The City University of Hong Kong researcher reports “in years with a high frequency of occurrence of intense typhoons, both the dynamic (relative vorticity in both the lower and upper troposphere as well as the vertical wind shear) and thermodynamic (as represented by the moist static energy in the low to mid troposphere) conditions in the atmosphere, especially in the eastern part of the WNP, are favorable for the formation of TCs [tropical cyclones],” and “once formed, these TCs tend to have longer lifetimes over the ocean, and therefore have a high chance to become more intense.” In addition, he notes the factors responsible for increasing the number of strong TCs are “also significantly correlated with the Niño3.4 SST anomalies.” Consequently, Chan reports, “the frequency of occurrence of intense typhoons in this region is not likely determined by the average SST over the region,” which is what would be expected to increase in response to greenhouse gas-induced global warming. Chan’s primary finding—that “interannual variations of intense typhoons in the WNP are likely caused to a large extent by changes in the planetary-scale atmospheric circulation and thermodynamic structure associated with the El Niño phenomenon”—provides no support for the contentions of either Emanuel (2005) or Webster *et al.* (2005).

Nott (2007) notes, “in tropical Australia, palaeo-tropical cyclone records occur in the form of low-resolution millennial-scale sedimentary ridges and high-resolution centennial-scale stalagmite records of isotopically depleted tropical cyclone rainfall.” He recounts the findings of those records and discusses their relevance to risk assessment and their role in “decoupling human induced changes in cyclone behavior from natural variability.” He states the clear message of the several papers he reviews is “the historical/instrumental record substantially under-

estimates the frequency of the most extreme tropical cyclone events,” citing the findings of Chappell *et al.* (1983), Chivas *et al.* (1986), Hayne and Chappell (2001), Nott and Hayne (2001), and Nott *et al.* (2007). He notes “tropical cyclone activity in north-east Queensland has been in a phase of quiescence since before European settlement of the region” and “the period between AD 1600 and 1800 [during the Little Ice Age] had many more intense or hazardous cyclones impacting the site than the post AD 1800 period.”

In addition, Nott notes the first 200 years of the tropical cyclone record—from AD 1200 to 1400, which represents the latter part of the Medieval Warm Period (MWP)—had the fewest intense cyclones. According to the criterion he used to define them, this period of significant global warmth had none, as did the latter decades of the twentieth century. He found the entire twentieth century had but one such intense cyclone, in 1911, whereas there were as many as seven intense tropical cyclones during the global chill that prevailed between AD 1600 and 1800.

Chan (2008) further investigated possible causes of the multidecadal variability in intense TC [category 4 and 5] occurrence in the WNP, choosing this basin because it generally has the largest number of TCs each year. Based on data for the period 1960–2005, he determined decadal variations in intense typhoon activity largely resulted from a combination of the behavior of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). This finding led him to suggest “the view that global warming would lead to more intense TCs owing to the enhancement of thermodynamic factors ignores the fact that for TCs to intensify significantly, the dynamic factors must ‘cooperate,’” which he notes has not been demonstrated to occur basin-wide. Therefore, he continues, “the more likely conclusion is that the major low-frequency variations in the frequency of intense TC occurrence is probably a multi-decadal one in response to similar variations in the factors that govern the formation, intensification and movement of TCs,” and “such variations largely result from modifications of the atmospheric and oceanographic conditions in response to ENSO and PDO.” Consequently, “at least for the WNP,” Chan notes, “it is not possible to conclude that the variations in intense typhoon activity are attributable to the effect of global warming.”

Defining rapid intensification (RI) of a tropical cyclone as occurring when the maximum wind speed of a TC “reaches at least (a) 5 knots in the first 6

hours, (b) 10 knots in the first 12 hours, and (c) 30 knots in 24 hours,” Wang and Zhou (2008) state “all category 4 and 5 hurricanes in the Atlantic basin and 90% of the equivalent-strength typhoons in the western North Pacific experience at least one RI process in their life cycles.” Using best-track TC data obtained from the Joint Typhoon Warning Center for the 40-year period 1965–2004, Wang and Zhou determined the climatic conditions most critical for the development of RI in TCs of the Western North Pacific on annual, intra-seasonal, and interannual time scales. They found “over the past 40 years, the annual total of RI in the western North Pacific shows pronounced interdecadal variation but no significant trend,” and they note this “implies that the super typhoons had likely no upward trend in the last 40 years.” In addition, they found “when the mean latitude, where the tropical storms form, shifted southward (either seasonally or from year to year), the proportion of super typhoons or major hurricanes will increase,” noting “this finding contrasts the current notion that higher sea surface temperature leads to more frequent occurrence of category 4 or 5 hurricanes.”

Englehart *et al.* (2008) developed a “first cut” dataset pertaining to the area immediately adjacent to Mexico’s Pacific coast. Although noting only 54% of the total number of Eastern Pacific storms reached TC status within this near-shore area over the period 1967–2005, they report “near-shore storm activity is fairly well correlated with total basin TC activity, a result which suggests that over the longer period (i.e., 1921-onward), changes in near-shore activity can provide some sense of the broader basin activity.” Their study revealed the existence of significant decadal variability in annual eastern Pacific near-shore TC frequency of occurrence. In addition, they found “long-term TC frequency exhibits a significant ($p = 0.05$) negative trend,” which, as best can be determined from their graph of the data, declines by about 23% over the 85-year period 1921–2005. This result was driven solely by an approximate 30% drop in TC frequency during the late (August–November) TC season, with essentially no long-term trend in the early (May–July) TC season.

Englehart *et al.* present a graph of the maximum wind speed associated with each TC, from which one can calculate an approximate 20% decline in this intensity-related parameter over the period of their study. Their work provides no support for the claim that global warming increases the frequency and intensity of TCs and/or hurricanes.

Hassim and Walsh (2008) analyzed TC best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) and off Queensland and the Gulf of Carpentaria (the eastern sector: 135–160°E, Pacific Ocean) for the presence of systematic intensity and duration trends over the cyclone season periods running from 1969–1970 through 2004–2005. The two Australian researchers report “substantial differences in trends are found between the two sub-regions, with the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones increasing since 1980 in the west but decreasing (in number) or exhibiting no trend (in intensity, severe category duration) in the east.”

Lu *et al.* (2008) also studied Western North Pacific (WNP) TCs during this time period, noting the WNP “is an area where typhoon activity is the most frequent and strongest” and “China is one of the countries that seriously suffered from typhoons in this area.” Using TC data “in the yearbooks of TC of the WNP from 1960 to 2005,” they analyzed the interdecadal variation of WNP TCs and the large-scale circulation factors affecting them. This analysis revealed “the time period from 1960 to 2005 has two high frequency periods (HFPs) and two low frequency periods (LFPs),” with the overall trend being downward (see Figure 7.8.3.1).

One year later, noting “the variability of TC activity (including the frequency of occurrence and intensity) has become a great concern because it may be affected by global warming,” Kubota and Chan (2009) created a unique dataset of TLP (tropical cyclone landfall numbers in the Philippines) based on historical observations of TC tracks during the period 1901–1940 obtained from monthly bulletins of the Philippine Weather Bureau and combined with TLP data obtained from the Joint Typhoon Warning Center for the period 1945–2005, which they used to investigate the TC-global warming hypothesis. The two Asian researchers found “the TLP has an apparent oscillation of about 32 years before 1939 and an oscillation of about 10–22 years after 1945,” but “no long-term trend is found.” In addition, they determined “natural variability related to ENSO and PDO phases appears to prevail in the interdecadal variability of TLP,” and their results show all variability was merely oscillatory activity around a mean trend of zero slope (see Figure 7.8.3.2).

Ma and Chen (2009) used NCEP/NCAR

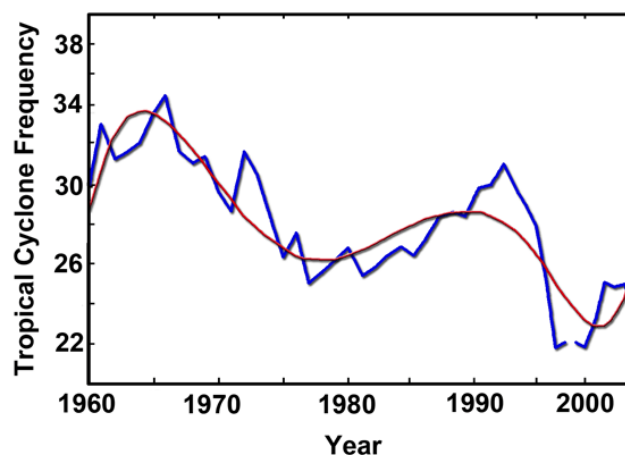


Figure 7.8.3.1. Tropical cyclone frequency vs. year. Blue line represents five-year running means, while the red line is a fifth-order polynomial that has been fitted to the data points. Adapted from Lu, Q-z., Hu, B-h., Wang, J. and Zhang, Y. 2008. Impact of large-scale circulation on the interdecadal variations of the western North Pacific tropical cyclone. *Journal of Tropical Meteorology* 14: 1006–8775(2008) 01-0081-04.

reanalysis data to determine the SST distribution over this region and to evaluate its temporal variability, utilizing TC frequency data obtained from the Joint Typhoon Warning Center, the *Tropical Cyclone Year Book* of the China Meteorological Administration, and the Tokyo-Typhoon Center of the Japanese Meteorological Agency to characterize TC frequency over the period 1949–2007. This work revealed, “SSTs over the WNP have been gradually increasing during the past 60 years ... with a maximum increment of 1°C around the central equatorial Pacific for the last 10 years.” They also state “the warm pool, which is defined to be enclosed by a critical temperature of 28°C, has expanded eastward and northward in recent years,” noting further “there has been remarkable warming in the last decade, more than 0.8°C in some local areas.” Nevertheless, and in spite of this “remarkable warming,” the two researchers determined “the frequency of TC against the background of global warming has decreased with time.”

Chan and Xu (2009) used TC data obtained from the Joint Typhoon Warning Center for the period 1945–2004 and the *Annual Tropical Cyclone Data Book* (edited by the Shanghai Typhoon Institute) for the period 1951–2000 to conduct a comprehensive study of variations in the annual number of landfalling TCs in three sub-regions of East Asia: South (south China, Vietnam, and the Philippines),

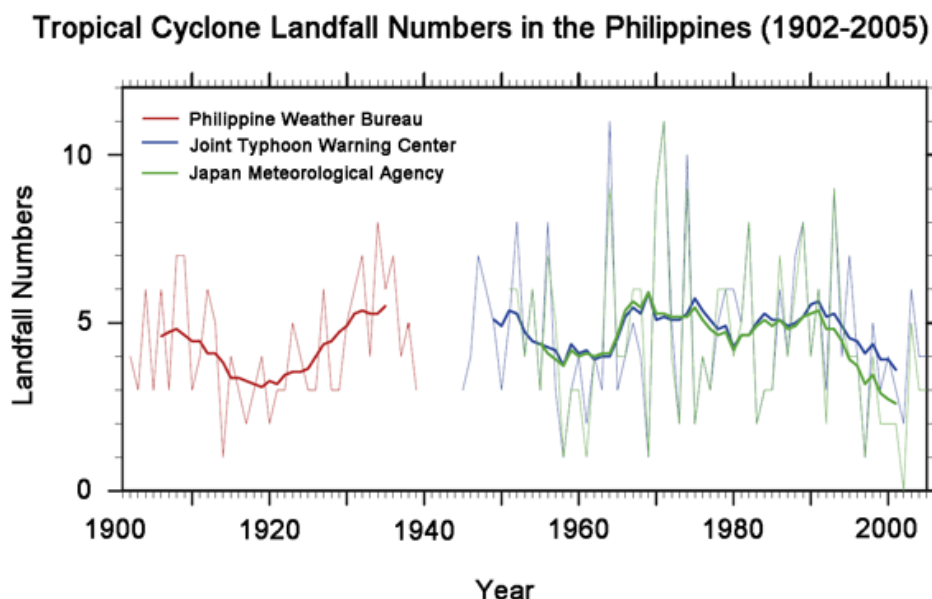


Figure 7.8.3.2. Tropical cyclone landfall numbers in the Philippines over the period 1902-2005. Adapted from Kubota, H. and Chan, J.C.L. 2009. Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. *Geophysical Research Letters* **36**: 10.1029/2009GL038108.

Middle (east China), and North (Korean Peninsula and Japan). They report “wavelet analyses of each time series show that the landfalling frequencies go through large inter-annual (2–8 years), inter-decadal (8–16 years) and even multi-decadal (16–32 years) variations, with the inter-annual being the most dominant, and the multi-decadal explaining most of the rest of the variance.” In what they call “an important finding,” they state “none of the time series shows a significant linear temporal trend, which suggests that global warming has not led to more landfalls in any of the regions in Asia.”

Song *et al.* (2010) point out, “in recent years, there has been increasing interest in whether global warming is enhancing tropical cyclone (TC) activity,” as has been claimed by Emanuel (2005) and Webster *et al.* (2005). They note Wu *et al.* (2006) and Yeung (2006) found “no increase in category 4–5 typhoon activity in the western North Pacific basin,” “in contrast to Webster *et al.* (2005).”

In addition, Song *et al.* report “neither RSMC nor HKO best track data suggest an increase in TC destructiveness.” They further state “other studies also examined the differences in TC data sets from the Joint Typhoon Warning Center (JTWC) of the U.S. Naval Pacific Meteorology Oceanography Center in Hawaii, the RSMC, and the Shanghai Typhoon Institute (STI) of [the] China

Meteorological Administration in Shanghai (Lei, 2001; Kamahori *et al.*, 2006; Ott, 2006; Yu *et al.*, 2007),” and “so far, the reported trends in TC activity in the WNP basin have been detected mainly in the JTWC best track data set,” which was the one employed by Emanuel (2005) and Webster *et al.* (2005) in drawing their anomalous conclusions.

To help resolve the anomalies exhibited by the JTWC typhoon database, Song *et al.* analyzed differences in track, intensity, frequency, and the associated long-term trends of those TCs that were simultaneously recorded and included within the best track data sets of the JTWC, the RSMC, and the STI from 1945 to 2007. They determined “though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2–3 as category 4–5, leading to an upward trend in the annual frequency of category 4–5 TCs and the annual accumulated power dissipation index, as reported by Webster *et al.* (2005) and Emanuel (2005).” They state “this trend and potential destructiveness over the period 1977–2007 are found only with the JTWC data set,” while noting downward trends “are apparent in the RSMC and STI data sets.”

Fengjin and Ziniu (2010) used data obtained from the China Meteorological Administration on the time and site of TC generation and landfall, TC tracks, and

the intensity and duration of TCs in the WNP and China for the period 1951–2008 to analyze the characteristics of TCs making landfall in China over that period. This work revealed “a decreasing trend in the generation of TCs in the WNP since the 1980s,” and they note the number of TCs making landfall during this period “has remained constant or shown only a slight decreasing trend.” They also report “the number of casualties caused by TCs in China appears to show a slight decreasing trend.”

Terry and Gienko (2010) analyzed various cyclone characteristics based on four decades of cyclone season data (1969–1970 to 2007–2008) in the regional cyclone archive of the tropical South Pacific (160°E–120°W, 0°–25°S) maintained by the Regional Specialized Meteorological Centre (RSMC) located at Nadi in the Fiji Islands. They state “no linear trends were revealed in cyclogenesis origins, cyclone duration, track length or track azimuth over the four decades of records,” but “anomalous activity for one or more cyclone parameters occurred in 1976, 1981, 1983, 1991, 1998, 2001–2002 and 2003,” leading them to conclude “there is as yet no evidence for climate-change forcing of these storm characteristics over recent historical times.”

Sun *et al.* (2011) analyzed data pertaining to TCs over the northwestern Pacific and the South China Sea, obtained from China’s Shanghai Typhoon Institute and the National Climate Center of the China Meteorological Administration, pertaining to the period 1951 to 2005. They determined the frequency of all TCs impacting China “tended to decrease from 1951 to 2005, with the lowest frequency [occurring] in the past ten years” (see Figure 7.8.3.3). In addition, they state the average yearly number of super typhoons was “three in the 1950s and 1960s” but “less than one in the past ten years.” They write “the decrease in the frequency of super typhoons, at a rate of 0.4 every ten years, is particularly significant (surpassing the significance test at the 0.01 level)” (see Figure 7.8.3.4), adding “there is a decreasing trend with the extreme intensity of these TCs during the period of influence in the past 55 years.”

Callaghan and Power (2011) developed and used “a new data base of severe land-falling TCs for eastern Australia derived from numerous historical sources, that has taken over a decade to develop.” This database, they continue, includes “peer-reviewed publications; Bureau of Meteorology publications, including comprehensive case histories for a large number of TCs – including all TCs since the mid-1950s, *Monthly Climatological Bulletins* and *Monthly*

Weather Reviews, unpublished TC season reports, bounded operational analysis charts back to the 1890s stored in the National Archives, unpublished internal Bureau documents; publications by state and local governments; archives of several Queensland newspapers; newspaper clippings held by the Bureau of Meteorology; books describing land-falling TCs; information held by the Cairns and Townsville Historical Societies; a report to the QLD parliament (1918); and extensive unpublished information from the public including numerous damage photographs,” as well as “reports on storm surge, wave action and shipwreck data from an extensive Australian shipwreck data base.”

The two researchers with Australia’s Bureau of Meteorology note their new database allows them “to document changes over much longer periods than has been done previously for the Southern Hemisphere.” Among the host of results they describe, two of them stand out with respect to their significance to the global warming debate. First, they report “the sign and magnitude of trends calculated over 30 years periods vary substantially,” noting “caution needs to be taken in making inferences based on *e.g.* satellite era data only.” Second, they report “the linear trend in the number of severe TCs making land-fall over eastern Australia declined from about 0.45 TC/year in the early 1870s to about 0.17 TC/year in recent times—a 62% decline.” They note “this decline can be partially explained by a weakening of the Walker Circulation, and a natural shift towards a more El Niño-dominated era.” Thus they conclude the abstract of their paper by saying, “the extent to which global warming might also be partially responsible for the decline in land-falls—if it is at all—is unknown,” suggesting global warming might be doing just the opposite of what climate models typically suggest it should do.

Noting the Intergovernmental Panel on Climate Change (IPCC, 2001, 2007) has twice suggested “precipitation and extreme winds associated with tropical cyclones may have become more intense,” Ying *et al.* (2011) remind us this claim is “mainly based on numerical models.” Working with tropical cyclone best track and related observational severe wind and precipitation datasets created by the Shanghai Typhoon Institute of the China Meteorological Administration, the four researchers identified trends in observed TC characteristics over the period 1955 to 2006 for the whole of China and four sub-regions: South China (SC), comprising Guangdong, Guangxi, and Hainan Provinces; East

Observations: Extreme Weather

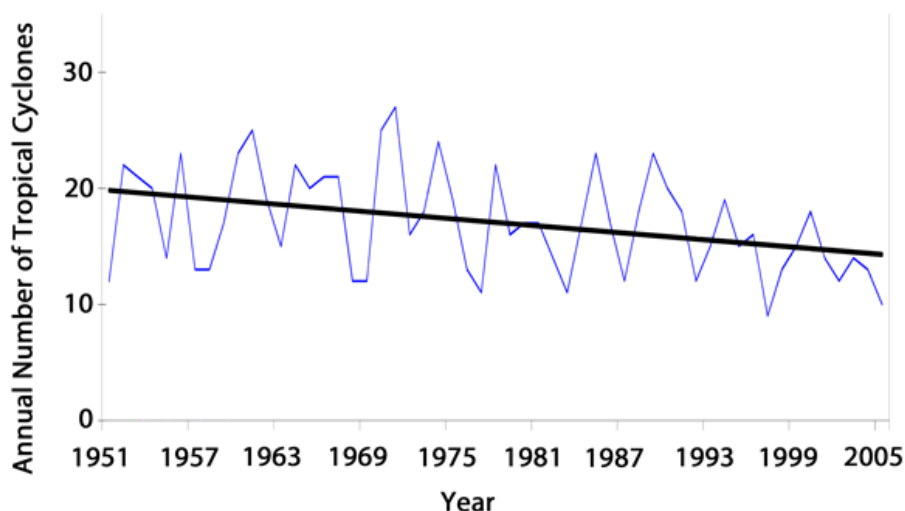


Figure 7.8.3.3. Number of typhoons affecting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* 17: 181-186.

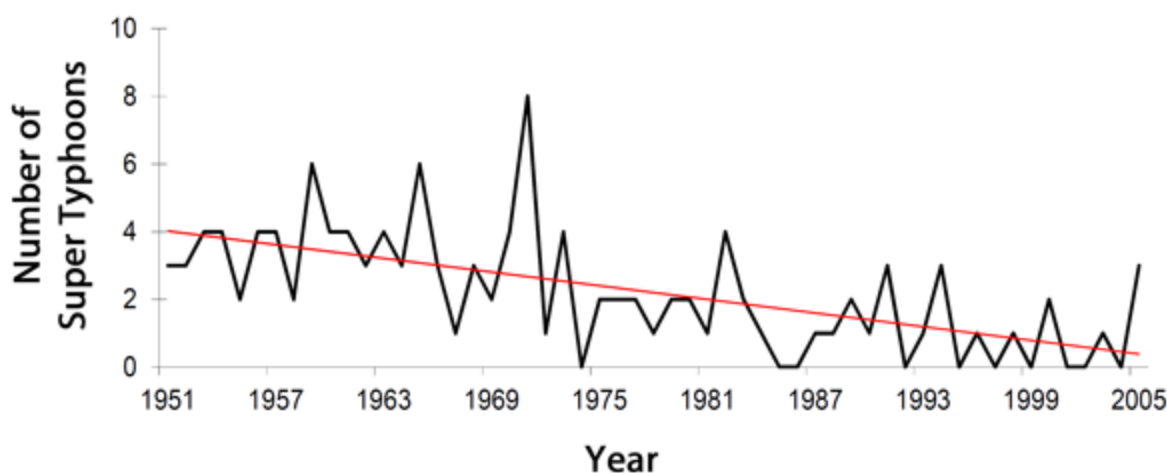


Figure 7.8.3.4. Frequency of super typhoons impacting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* 17: 181-186.

China (EC), comprising Fujian, Hiangxi, Zhejiang, Anhui, Jiangsu, and Shandong Provinces plus Shanghai; Northeast China (NEC), comprising Liaoning, Jilin, and Heilongjiang Provinces; and China's inland area (CI) including all remaining provinces.

They found over the past half-century there have been no changes in the frequency of TC occurrence, except within NEC, where they determined “years with a high frequency of TC influence have significantly become less common.” They also note, “during the past 50 years, there have been no

significant trends in the days of TC influence on China” and “the seasonal rhythm of the TC influence on China also has not changed.” They found “the maximum sustained winds of TCs affecting the whole of China and all sub-regions have decreasing trends” and “the trends of extreme storm precipitation and 1-hour precipitation were all insignificant.” Thus, for the whole of China and essentially all of its component parts, major measures of TC impact have remained constant or slightly decreased, a much different consequence from what the IPCC has been predicting for the world over the past decade or more.

Xiao *et al.* (2011) “developed a Tropical Cyclone Potential Impact Index (TCPI) based on the air mass trajectories, disaster information, intensity, duration and frequency of tropical cyclones,” using observational data obtained from the China Meteorological Administration’s *Yearbook of Tropical (Typhoon) Cyclones in China* for the years 1951–2009 plus the *Annual Climate Impact Assessment* and *Yearbook of Meteorological Disasters* in China, also compiled by the China Meteorological Administration, but for the years 2005–2009. The five researchers report “China’s TCPI appears to be a weak decreasing trend over the period [1949–2009], which is not significant overall, but significant in some periods.”

Ren *et al.* (2011) write “the homogeneity of historical observations is important in the study of tropical cyclones and climate change,” with “a large hurdle for climate change detection” being “the quality of TC historical databases,” which they say “were populated over time without a focus on maintaining data homogeneity,” “a key requirement for databases that are used to assess possible climate-related trends.” In an effort to overcome this hurdle, which they describe as “a ‘bottleneck’ in tropical cyclone and climate change studies,” Ren *et al.* analyze three historical datasets for Western North Pacific TCs—those of the Joint Typhoon Warning Center (JTWC), the Japan Meteorological Agency (JMA), and the China Meteorological Administration (CMA)—focusing primarily on TC intensity and covering the 55-year period 1951–2005.

The five researchers conclude “it is still difficult to judge which one [of the three datasets] is best.” They indicate frequencies of the common TCs in all three datasets “show no obvious increasing or decreasing trend over the past 50 years.” Instead, they find a weak interdecadal variation with “more TCs from the mid-1960s to the mid-1970s and in the early 1990s.” By contrast, they state the intensities of the common TCs “differed largely from one dataset to another, leading to quite opposite conclusions for TCs of category 4 and 5.” For example, they note “for the period after 1970, the JTWC dataset shows an increasing trend that complies with those of Webster *et al.* (2005) and Emanuel (2005),” but “for a longer time scale, the result may be well consistent with that of Chan (2006),” which suggests “the so-called ‘trend’ is a fragment of the longer inter-decadal variation.”

Zhang *et al.* (2011) analyzed both the frequency and intensity of TCs that made landfall on the Pacific coast of South China’s Guangdong Province between

1965 and 2007. Employing data extracted from the database collected by the Shanghai Typhoon Institute of the China Meteorological Administration, together with pertinent sea surface temperature (SST) data for the Pacific Ocean obtained from the UK Met Office’s Hadley Centre, the four Chinese researchers studied the changing properties of the frequency and intensity of the TCs making landfall at the Guangdong Province (TMLGP) as functions of time and temperature.

They found the frequency of TMLGP after 1996 had “a nearly opposite trend compared to the period preceding 1996” and determined “the frequency of TMLGP for the period 1965–2007 as a whole is in an insignificant relation with SST in these two periods.” They also found various SST measures “only have a weak influence on TMLGP intensities.” They note, “despite the long-term warming trend in SST in the Western North Pacific, no long-term trend is observed in either the frequency or intensities of TMLGP.”

References

- Bister, M. and Emanuel, K. 2002. Low frequency variability of tropical cyclone potential intensity. 1. Interannual to interdecadal variability. *Journal of Geophysical Research* **107**: 10.1029/2001JD000776.
- Callaghan, J. and Power, S.B. 2011. Variability and decline in the number of severe tropical cyclones making land-fall over eastern Australia since the late nineteenth century. *Climate Dynamics* **37**: 647–662.
- Chan, J.C.L. 2006. Comment on “Changes in tropical cyclone number, duration, and intensity in a warming environment.” *Science* **311**: 1713.
- Chan, J.C.L. 2007. Interannual variations of intense typhoon activity. *Tellus* **59A**: 455–460.
- Chan, J.C.L. 2008. Decadal variations of intense typhoon occurrence in the western North Pacific. *Proceedings of the Royal Society A* **464**: 249–272.
- Chan, J.C.L. and Liu, K.S. 2004. Global warming and western North Pacific typhoon activity from an observational perspective. *Journal of Climate* **17**: 4590–4602.
- Chan, J.C.L. and Xu, M. 2009. Inter-annual and inter-decadal variations of landfalling tropical cyclones in East Asia. Part I: time series analysis. *International Journal of Climatology* **29**: 1285–1293.
- Chappell, J., Chivas, A., Rhodes, E., and Wallensky, E. 1983. Holocene palaeo-environmental changes, central to north Great Barrier Reef inner zone. *Journal of Australian Geology and Geophysics* **8**: 223–235.

Observations: Extreme Weather

- Chivas, A., Chappell, J., and Wallensky, E. 1986. Radiocarbon evidence for the timing and rate of island development, beach rock formation and phosphatization at Lady Elliot Island, Queensland, Australia. *Marine Geology* **69**: 273–287.
- Chu, P.-S. and Clark, J.D. 1999. Decadal variations of tropical cyclone activity over the central North Pacific. *Bulletin of the American Meteorological Society* **80**: 1875–1881.
- Emanuel, K.A. 1986. An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *Journal of the Atmospheric Sciences* **43**: 585–604.
- Emanuel, K.A. 1995. Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *Journal of the Atmospheric Sciences* **52**: 3969–3976.
- Emanuel, K.A. 1999. Thermodynamic control of hurricane intensity. *Nature* **401**: 665–669.
- Emanuel, K.A. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.
- Englehart, P.J., Lewis, M.D., and Douglas, A.V. 2008. Defining the frequency of near-shore tropical cyclone activity in the eastern North Pacific from historical surface observations (1921–2005). *Geophysical Research Letters* **35**: 10.1029/2007GL032546.
- Free, M., Bister, M., and Emanuel, K. 2004. Potential intensity of tropical cyclones: comparison of results from radiosonde and reanalysis data. *Journal of Climate* **17**: 1722–1727.
- Hall, J.D. 2004. The South Pacific and southeast Indian Ocean tropical cyclone season 2001–02. *Australian Meteorological Magazine* **53**: 285–304.
- Hassim, M.E.E. and Walsh, K.J.E. 2008. Tropical cyclone trends in the Australian region. *Geochemistry, Geophysics, Geosystems* **9**: 10.1029/2007GC001804.
- Hayne, M. and Chappell, J. 2001. Cyclone frequency during the last 5000 years at Curacoa Island, north Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **168**: 207–219.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- Kamahori, H., Yamazaki, N., Mannoji, N., and Takahashi, K. 2006. Variability in intense tropical cyclone days in the western North Pacific. *SOLA* **2**: 104–107.
- Kubota, H. and Chan, J.C.L. 2009. Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. *Geophysical Research Letters* **36**: 10.1029/2009GL038108.
- Lei, X. 2001. The precision analysis of the best positioning on WNP TC. *Journal of Tropical Meteorology* **17**: 65–70.
- Li, Y., Wang, X., Yu, R., and Qin, Z. 2007. Analysis and prognosis of tropical cyclone genesis over the western North Pacific on the background of global warming. *Acta Oceanologica Sinica* **26**: 23–34.
- Liu, K.-b., Shen, C., and Louie, K.-s. 2001. A 1,000-year history of typhoon landfalls in Guangdong, southern China, reconstructed from Chinese historical documentary records. *Annals of the Association of American Geographers* **91**: 453–464.
- Lu, Q.-z., Hu, B.-h., Wang, J., and Zhang, Y. 2008. Impact of large-scale circulation on the interdecadal variations of the western North Pacific tropical cyclone. *Journal of Tropical Meteorology* **14**: 1006–8775(2008) 01-0081-04.
- Nott, J. 2007. The importance of Quaternary records in reducing risk from tropical cyclones. *Palaeogeography, Palaeoclimatology, Palaeoecology* **251**: 137–149.
- Nott, J., Haig, J., Neil, H., and Gillieson, D. 2007. Greater frequency variability of landfalling tropical cyclones at centennial compared to seasonal and decadal scales. *Earth and Planetary Science Letters* **255**: 367–372.
- Nott, J. and Hayne, M. 2001. High frequency of ‘super-cyclones’ along the Great Barrier Reef over the past 5,000 years. *Nature* **413**: 508–512.
- Ott, S. 2006. Extreme Winds in the Western North Pacific. *Rep. Rise-R-1544(EN)*, Riso National Laboratory, Technical University of Denmark, Copenhagen.
- Ren, F., Liang, J., Wu, G., Dong, W., and Yang, X. 2011. Reliability analysis of climate change of tropical cyclone activity over the Western North Pacific. *Journal of Climate* **24**: 5887–5898.
- Ren, F., Wu, G., Dong, W., Wang, X., Wang, Y., Ai, W., and Li, W. 2006. Changes in tropical cyclone precipitation over China. *Geophysical Research Letters* **33**: 10.1029/2006GL027951.
- Song, J.-J., Wang, Y., and Wu, L. 2010. Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. *Journal of Geophysical Research* **115**: 10.1029/2009JD013058.
- Sun, L.-h., Ai, W.-x., Song, W.-l., and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing

tropical cyclones. *Journal of Tropical Meteorology* **17**: 181–186.

Terry, J.P. and Gienko, G. 2010. Climatological aspects of South Pacific tropical cyclones, based on analysis of the RSMC-Nadi (Fiji) regional archive. *Climate Research* **42**: 223–233.

Wang, B. and Zhou, X. 2008. Climate variation and prediction of rapid intensification in tropical cyclones in the western North Pacific. *Meteorology and Atmospheric Physics* **99**: 1–16.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846.

Wu, M.-C., Yeung, K.-H., and Chang, W.-L. 2006. Trends in western North Pacific tropical cyclone intensity. *EOS, Transactions, American Geophysical Union* **87**: 537–538.

Xiao, F., Yin, Y., Luo, Y., Song, L., and Ye, D. 2011. Tropical cyclone hazards analysis based on tropical cyclone potential impact index. *Journal of Geographical Sciences* **21**: 791–800.

Yeung, K.H. 2006. Issues related to global warming—Myths, realities and warnings. Paper presented at the 5th Conference on Catastrophe in Asia, Hong Kong Observatory, Hong Kong, China, 20–21 June.

Ying, M., Yang, Y.-H., Chen, B.-D., and Zhang, W. 2011. Climatic variation of tropical cyclones affecting China during the past 50 years. *Science China Earth Sciences* **54**: 10.1007/s11430-011-4213-2.

Yu, H., Hu, C., and Jiang, L. 2007. Comparison of three tropical cyclone intensity datasets. *Acta Meteorologica Sinica* **21**: 121–128.

Zhang, Q., Zhang, W., Lu, X., and Chen, Y.D. 2011. Landfalling tropical cyclones activities in the south China: intensifying or weakening? *International Journal of Climatology* **32**: 1815–1924.

7.8.4 Global

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO₂-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the entire globe.

Climate models have long suggested the intensity and frequency of hurricanes or tropical cyclones (TCs) may be significantly increased in response to global warming, as noted by Free *et al.* (2004), who

have written “increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming,” citing in support of this statement the studies of Emanuel (1987), Henderson-Sellers *et al.* (1998), and Knutson *et al.* (1998). Before accepting this climate-model-based projection, it is important to consider what drives tropical cyclone activity in the real world.

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) conclude “the effect of global warming on the number of tropical cyclones is presently unknown,” and “there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe.” They report there is “little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers.”

In a second early analysis of the topic, Henderson-Sellers *et al.* (1998) determined “there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses,” “global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill,” and “the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy.”

Walsh (2004) acknowledged “there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming.” Nevertheless, Walsh suggested “there is likely to be some increase in maximum tropical cyclone intensities in a warmer world,” “it is probable that this would be accompanied by increases in mean tropical cyclone intensities,” and “these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%.” He put the date of possible detection of these increases “sometime after 2050,” little knowing two such claims would be made the very next year.

The historic contentions came from Emanuel (2005), who claimed to have found a hurricane power dissipation index had increased by approximately 50% for the Atlantic basin and the Northwest Pacific basin since the mid-1970s, and from Webster *et al.* (2005), who contended the number of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975–1989) and a more recent (1990–2004) 15-year period. In a challenge to both these claims, Klotzbach (2006) wrote “many

Observations: Extreme Weather

questions have been raised regarding the data quality in the earlier part of their analysis periods,” and he performed a new analysis based on a “near-homogeneous” global dataset for the period 1986–2005.

Klotzbach first tabulated global tropical cyclone (TC) activity using best track data, which he described as “the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers,” for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian, and South Pacific). He then determined trends of worldwide TC frequency and intensity over the period 1986–2005, during which time global SSTs are purported to have risen by about 0.2–0.4°C. Klotzbach found “a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin,” but also “a considerable decreasing trend for the Northeast Pacific.” Combining these observations with the fact that “all other basins showed small trends,” he concluded there had been “no significant change in global net tropical cyclone activity” over the past two decades.

With respect to Category 4 and 5 hurricanes, Klotzbach found there had been a “small increase” in their numbers from the first half of the study period (1986–1995) to the last half (1996–2005), but he noted “most of this increase is likely due to improved observational technology.” Klotzbach declared his findings were “contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al.* (2005),” in that the global TC data did “not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years.”

Landsea *et al.* (2006) asked whether “the global tropical cyclone databases [are] sufficiently reliable to ascertain long-term trends in tropical cyclone intensity, particularly in the frequency of extreme tropical cyclones (categories 4 and 5 on the Saffir-Simpson Hurricane Scale).” They analyzed the history of a number of operational changes at various tropical cyclone warning centers they theorized might have led to “more frequent identification of extreme tropical cyclones,” as well as an unreal “shift to stronger maximum sustained surface wind,” investigating in particular in this regard the Dorvak Technique for estimating tropical cyclone intensity.

The four researchers found “trend analyses for extreme tropical cyclones are unreliable because of operational changes that have artificially resulted in more intense tropical cyclones being recorded [with

the passing of time], casting severe doubts on any such trend linkages to global warming.” In addition, they note “data from the only two basins that have had regular aircraft reconnaissance—the Atlantic and Northwest Pacific—show that no significant trends exist in tropical cyclone activity when records back to at least 1960 are examined (Landsea, 2005; Chan, 2006),” while additionally noting “Klotzbach (2006) has shown that extreme tropical cyclones and overall tropical cyclone activity have globally been flat from 1986 until 2005, despite a sea surface temperature warming of 0.25°C.”

Kossin *et al.* (2007) note “the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous,” adding this “known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates.” As an important first step in resolving this problem, Kossin *et al.* “constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates.” They analyzed the resultant homogenized data for temporal trends over the period 1984–2004 for all major ocean basins and the global ocean as a whole.

The five scientists report, “using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic.” Therefore, noting “the Atlantic basin accounts for less than 15% of global hurricane activity,” they conclude “this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity.” They concluded, “the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future.”

Vecchi and Soden (2007) used climate models and real-world observations “to explore the relationship between changes in sea surface temperature and tropical cyclone ‘potential intensity’—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development.” They conclude “changes in local sea surface temperature are inadequate for characterizing

even the sign of changes in potential intensity.”

Reporting on the International Summit on Hurricanes and Climate Change held in May 2007 on the Greek island of Crete, where 77 academics and stakeholders from 18 countries participated in a free-ranging discussion of hurricanes and climate change, Elsner (2008) writes, “the question of whether we can ascribe a change in tropical cyclone intensity to anthropogenic climate change is still open.” On the question of a warming-induced increase in hurricane frequency, he states the science was even more unsettled. Although “most models,” in his words, indicate “an overall decrease in the number of storms,” he notes not even all models agree on the change in individual basin tropical cyclone numbers, “with some models showing an increase in the Atlantic and others a decrease.”

Further confusion was raised by Nolan and Rappin (2008), who extended the methodology of Nolan *et al.* (2007) to include a prescribed wind as a function of height that remains approximately constant during the genesis of tropical cyclones in environments of radiative-convective equilibrium partially defined by sea surface temperature (SST). They employed the modified methodology to explore what happens when SSTs rise. This approach revealed “increasing sea surface temperature does not allow TC genesis to overcome greater shear.” In fact, they note “the opposite trend is found,” and “the new and surprising result of this study is that the effect of shear in suppressing TC genesis actually increases as the SST of the radiative-convective equilibrium environment is increased.”

This model-based finding was analogous to the observation-based result of Vecchi and Knutson (2008), who found as the SST of the main development region of North Atlantic TCs had increased over the past 125 years, certain aspects of climate changed in ways that may have made the North Atlantic “more favorable to cyclogenesis, while at the same time making the overall environment less favorable to TC maintenance.” It is interesting that Nolan and Rappin conclude their paper with the intriguing question, “Do these results explain recent general circulation modeling studies predicting fewer tropical cyclones in a global warming world (e.g., Bengtsson *et al.* 2007)?”

Fan and Liu (2008) present a brief review and synthesis of the major research advances and findings of paleotempestology, which they describe as “a young science” that “studies past typhoon activity spanning several centuries to millennia before the

instrumental era through the use of geological proxies and historical documentary records.” They found “there does not exist a simple linear relationship between typhoon frequency and Holocene climate (temperature) change,” especially of the type suggested by climate models. They report “on the contrary, typhoon frequency seemed to have increased at least regionally during the coldest phases of the Little Ice Age.” They also note “more typhoons and hurricanes make landfalls in China, Central and North America during [cooler] La Niña years than [warmer] El Niño years.” Consequently, and following their own advice about the need “to extend the time span of typhoon activity records” to help resolve the debate over the nature of climate change effects on this important weather phenomenon, Fan and Liu demonstrated the models likely have even the sign of the temperature effect on typhoon activity wrong, as global warming seems to reduce tropical cyclone activity over both the long term and the short term.

Chan (2009) studied five ocean basins—the Atlantic (1960–2007), Western North Pacific (1960–2007), Eastern North Pacific (1960–2007), South Indian Ocean (1981–2007), and South Pacific (1981–2007)—examining the relationship between the seasonally averaged maximum potential intensity (MPI, an index of thermodynamic forcing) over each basin and the frequency of occurrence of intense TCs within that basin. This work revealed “only in the Atlantic does the MPI have a statistically significant relationship with the number of intense TCs, explaining about 40% of the [observed] variance,” whereas “in other ocean basins, there is either no correlation or the correlation is not significant.” Even in the Atlantic, where a significant correlation exists between thermodynamic or temperature-related factors and the frequency of intense TCs, it is not clear whether global warming will produce a net increase in TC frequency, because model projections also suggest the increase in vertical wind shear associated with an increase in sea surface temperature tends to work against intense TC development. Therefore, Chan concludes, “it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario.”

Wang and Lee (2009) note in the Western Hemisphere, tropical cyclones “can form and develop in both the tropical North Atlantic (NA) and eastern North Pacific (ENP) Oceans, which are separated by the narrow landmass of Central America,” and “in comparison with TCs in the NA, TCs in the ENP have

Observations: Extreme Weather

received less attention, although TC activity is generally greater in the ENP than in the NA (e.g., Maloney and Hartmann, 2000; Romero-Vadillo *et al.*, 2007).” In exploring how the TC activities of the NA and ENP ocean basins might be related to each other over the periods 1949–2007 and 1979–2007, they employed several datasets to calculate the index of accumulated cyclone energy (ACE), which accounts for the number, strength, and duration of all TCs in a given season. They discovered “TC activity in the NA varies out-of-phase with that in the ENP on both interannual and multidecadal timescales,” so “when TC activity in the NA increases (decreases), TC activity in the ENP decreases (increases).” In addition, they found “the out-of-phase relationship seems to [have] become stronger in the recent decades.” The interannual and multidecadal correlations between the NA and ENP ACE indices were -0.70 and -0.43, respectively, for the period 1949–2007, but -0.79 and -0.59, respectively, for the period 1979–2007. In terms of the combined TC activity over the NA and ENP ocean basins as a whole, there is little variability on either interannual or multidecadal timescales. The real-world empirical data thus suggest the variability that does exist over the two basins has grown slightly weaker as Earth has warmed over the past six decades, running counter to claims that Earth’s hurricanes or tropical cyclones should become more numerous, stronger, and longer-lasting as temperatures rise.

Wang *et al.* (2010) examined cross-basin spatial-temporal variations of TC storm days for the Western North Pacific (WNP), Eastern North Pacific (ENP), North Atlantic (NAT), North Indian Ocean (NIO), and Southern Hemisphere Ocean (SHO) over the period 1965–2008, for which period satellite data were obtained from the U.S. Navy’s Joint Typhoon Warning Center for the WNP, NIO, and SHO, and from NASA’s U.S. National Hurricane Center for the NAT and ENP. They report “over the period of 1965–2008, the global TC activity, as measured by storm days, shows a large amplitude fluctuation regulated by the El Niño–Southern Oscillation and the Pacific Decadal Oscillation, but has no trend, suggesting that the rising temperature so far has not yet [had] an impact on the global total number of storm days.” This further implies “the spatial variation of SST, rather than the global mean temperature, may be more relevant to understanding the change of the global storm days.”

Maue (2011) obtained global TC life cycle data from the IBTrACS database of Knapp *et al.* (2010),

which contains six-hourly best-track positions and intensity estimates for the period 1970–2010, from which he calculated the accumulated cyclone energy (ACE) metric (Bell *et al.*, 2000), which is analogous to the power dissipation index (PDI) used by Emanuel (2005) in his attempt to link hurricanes with global warming. Maue found “in the pentad since 2006, Northern Hemisphere and global tropical cyclone ACE has decreased dramatically to the lowest levels since the late 1970s.” He also found “the global frequency of tropical cyclones has reached a historical low.” He noted “a total of 69 TCs were counted during calendar year 2010, the fewest observed in the past 40 years with reliable frequency data.” Over the four-decade period, “12-month running-sums of the number of global TCs of at least tropical storm force has averaged 87,” and “the minimum number of 64 TCs was recently tallied through May 2011.” Maue noted “there is no significant linear trend in the frequency of global TCs,” in agreement with the analysis of Wang *et al.* (2010). “[T]his current period of record inactivity,” as Maue describes it, suggests the long-held contention that global warming increases the frequency and intensity of tropical storms is simply not true.

Noting “Quaternary data have not figured prominently in recent debates concerning TC natural variability versus potential anthropogenic global warming-induced changes, nor have the Quaternary data been used to any substantial degree in numerical model projections concerning the future behavior of TCs,” Nott (2011) provided a brief review of the subject, writing there are “at least 15 different methods for reconstructing long-term records of TCs.”

The Australian researcher reports “recent analyses of corrected historical TC records suggest that there are no definitive trends towards an increase in the frequency of high-intensity TCs for the Atlantic Ocean region (Knutson *et al.*, 2010), the northwest Pacific (Chan, 2006; Kossin *et al.*, 2007) and the Australian region, South Pacific and south Indian oceans (Kuleshov *et al.*, 2010).” He points out, “over multi-century to millennial timescales, substantial change has occurred in virtually all TC-generating regions of the globe,” with “alternating periods of lesser and greater activity.” He notes “the longer, coarser-resolution records display periods from multi-century to over a millennium in length, whereas the higher-resolution records register multi-decadal to centennial-length periodicities.”

In some of these cases, Nott states, “different climate states, such as periods dominated by El Niños

and La Niñas, appear to be responsible for the TC variability,” whereas in other cases the responsible factor seems to be shifts in the position of the jet stream, solar variability, or some unknown cause. Nott notes “there is still considerably more data needed before causes of the long-term variability of TCs can be comprehensively identified” and “a better understanding of this long-term variability will be critical to understanding the likely future behavior of TCs globally and especially so when attempting to detect and attribute those future changes.”

In a study designed to explore “the question of whether and to what extent global warming may be changing tropical cyclone activity,” Grossmann and Morgan (2011) reviewed the scientific literature related to the possible effects on TC frequency and intensity of climate-model projected consequences of continued atmospheric greenhouse gas enrichment. They found “while Atlantic TCs have recently become more intense, evidence for changes in other basins is not persuasive, and changes in the Atlantic cannot be clearly attributed to either natural variability or climate change.” They state “the presence of a possible climate change signal in TC activity is difficult to detect because inter-annual variability necessitates analysis over longer time periods than available data allow,” and because “projections of future TC activity are hindered by computational limitations and uncertainties about changes in regional climate, large-scale patterns, and TC response.”

While noting “scientific uncertainty about whether and how climate change will affect TCs in the future may not be resolved for decades,” Grossmann and Morgan go on to suggest even if climate change “does not result in any significant increase in the intensity or frequency of future tropical cyclones” nor “lead to significant sea-level rise,” human vulnerability in areas prone to land-falling hurricanes “will likely continue to increase significantly due to the continuing growth of populations and capital stock in high risk areas,” citing Pielke *et al.* (2008). They conclude it would be wise “to induce greater protective action,” and “there is a need to act now to reduce the existing high vulnerability to these storms,” which will continue to constitute a real and present danger to people and infrastructure in coastal areas regardless of whether the frequency and degree of that danger increases or decreases.

Although many studies have explored the impacts of changes in sea surface temperature on various

properties of tropical cyclones, the reverse phenomenon—the impacts of TCs on SSTs—has been less discussed. It has been known for decades, however, as reported by Dare and McBride (2011), that strong winds associated with TCs tend to reduce SSTs beneath such storms, as described by Fisher (1958), Leipper (1967), Brand (1971), Price (1981), Bender *et al.* (1993), Hart *et al.* (2007), Price *et al.* (2008), Jansen *et al.* (2010), and Hart (2011). This cold surface wake, as they describe it, “may extend for hundreds of kilometers adjacent to the storm track (Nelson, 1996; Emanuel, 2001),” and it can spread to larger scales over time, as reported by Sobel and Camargo (2005). As for the magnitude of the SST reduction within the TC wake, Dare and McBride write it can “range from less than 1°C (Cione *et al.*, 2000), up to 3° (Shay *et al.*, 1991), 4° (Price *et al.*, 2008), 5° (Price, 1981), 6° (Berg, 2002), 7° (Walker *et al.*, 2005), and 9°C (Lin *et al.*, 2003).”

Using the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al.*, 2009) to provide the latitudes and longitudes at six-hour intervals for all TCs that occurred worldwide between September 1, 1981 and December, 31 2008, together with a corresponding set of SST data provided by NOAA’s National Climatic Data Center at every 0.25° of latitude and longitude (Reynolds *et al.*, 2007), Dare and McBride calculated the mean magnitude of the SST reductions and the average amount of time required for the reduced SSTs to return to pre-storm values. This effort revealed the time of maximum SST cooling occurred one day after cyclone passage, when the SST depression averaged 0.9°C. Thereafter, they report 44% of the SST depressions returned to normal within five days, while 88% of them recovered within 30 days. And although there were differences among individual cyclone basins, they say the individual basin results were in broad agreement with the global mean results. Finally, they report “cyclones occurring in the first half of the cyclone season disrupt the seasonal warming trend, which is not resumed until 20–30 days after cyclone passage,” while “cyclone occurrences in the latter half of the season bring about a 0.5°C temperature drop from which the ocean does not recover due to the seasonal cooling cycle.” Each TC occurring somewhere in the world leaves behind it a significantly altered SST environment that would be expected to have an effect 20 to 30 days later on other TCs that might pass through the same location.

Manucharyan *et al.* (2011) analyzed the effects of TCs on other TCs using several representative cases

of time-dependent mixing that yielded the same annual mean values of vertical diffusivity, conforming with the studies of Jansen and Ferrari (2009) and Fedorov *et al.* (2010), wherein spatially uniform (but varying in time) mixing is imposed on zonal bands in the upper ocean. This work revealed “a weak surface cooling at the location of the mixing ($\sim 0.3^{\circ}\text{C}$), a strong warming of the equatorial cold tongue ($\sim 2^{\circ}\text{C}$), and a moderate warming in middle to high latitudes (0.5°C – 1°C),” together with “a deepening of the tropical thermocline with subsurface temperature anomalies extending to 500 m [depth].” They state “additional mixing leads to an enhanced oceanic heat transport from the regions of increased mixing toward high latitudes and the equatorial region.” But “ultimately,” they continue, “simulations with TC-resolving climate models will be necessary to fully understand the role of tropical cyclones in climate,” for they note “the current generation of GCMs [is] only slowly approaching this limit and [is] still unable to reproduce many characteristics of the observed hurricanes, especially of the strongest storms critical for the ocean mixing (e.g., Gualdi *et al.*, 2008; Scoccimarro *et al.*, 2011).”

Nott and Forsyth (2012) write, “understanding the long-term natural variability of tropical cyclones (TCs) is important for forecasting their future behavior and for the detection and attribution of changes in their activity as a consequence of anthropogenically induced climate change.” They point out, “critical to these endeavors is determining whether, over the long-term, TCs occur randomly or display identifiable patterns influenced by one or several factors.”

The two researchers present “new sedimentary data from the southwest (SW) Pacific and southeast (SE) Indian Ocean regions which allow us to make comparisons with existing sediment records from the Atlantic Ocean (Donnelly and Woodruff, 2007; Mann *et al.*, 2009), northwest (NW) Pacific (Woodruff *et al.*, 2009), Gulf of Mexico (Liu and Fearn, 1993, 2000; Lane *et al.*, 2011) and the Gulf of Carpentaria, Australia (Rhodes *et al.*, 1980).” They find “long-term global TC activity is not random.” Instead, there is “a substantial degree of synchronicity in global intense TC behavior over the past 3,000 to 5,000 years.” And they report “one of the most striking aspects of these records is they all display extended alternating periods (centuries to millennia) of relative quiescence and heightened intense TC activity irrespective of both the resolution and type of long-term TC record.”

Something yet unknown has orchestrated the ebbing and flowing of global TC activity over the past 5,000 years. We do know it has not been changes in the atmosphere’s CO_2 concentration, which has remained relatively stable over this entire period except for the past 100 years, when it has risen substantially without any demonstrable change in global TC activity. There is no compelling reason to believe further increase in the air’s CO_2 content will have any significant impact on these destructive storms.

References

- Bell, G.D., Halpert, M.S., Schnell, R.C., Higgins, R.W., Lawrimore, J., Kousky, V.E., Tinker, R., Thiaw, W., Chelliah, M., and Artusa, A. 2000. Climate assessment for 1999. *Bulletin of the American Meteorology Society* **81**: S1–S50.
- Bender, M.A., Ginis, I., and Kurihara, Y. 1993. Numerical simulations of tropical cyclone-ocean interaction with a high-resolution coupled model. *Journal of Geophysical Research* **98**: 23,245–23,263.
- Bengtsson, L., Hodges, K.I., Esch, M., Keelyside, N., Kornbluehm, L., Luo, J.-J., and Yamagata, T. 2007. How may tropical cyclones change in a warmer climate? *Tellus Series A* **59**: 531–561.
- Berg, R. 2002. Tropical cyclone intensity in relation to SST and moisture variability: A global perspective. *Twenty-Fifth Conference on Hurricanes and Tropical Meteorology*. American Meteorological Society. Boston, Massachusetts, USA.
- Brand, S. 1971. The effects on a tropical cyclone of cooler surface waters due to upwelling and mixing produced by a prior tropical cyclone. *Journal of Applied Meteorology* **10**: 865–874.
- Chan, J.C.L. 2006. Comment on “Changes in tropical cyclone number, duration, and intensity in a warming environment.” *Science* **322**: 1713–1713b.
- Chan, J.C.L. 2009. Thermodynamic control on the climate of intense tropical cyclones. *Proceedings of the Royal Society A* **465**: 3011–3021.
- Cione, J.J., Molina, P., Kaplan, J., and Black, P.G. 2000. SST time series directly under tropical cyclones: Observations and implications. *Twenty-Fourth Conference on Hurricanes and Tropical Meteorology*. American Meteorological Society. Boston, Massachusetts, USA.
- Dare, R.A. and McBride, J.L. 2011. Sea surface temperature response to tropical cyclones. *Monthly Weather Review* **139**: 3798–3808.

Climate Change Reconsidered II

- Donnelly, J.P. and Woodruff, J.S. 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature* **447**: 465–468.
- Elsner, J.B. 2008. Hurricanes and climate change. *Bulletin of the American Meteorological Society* **89**: 677–679.
- Emanuel, K.A. 1987. The dependence of hurricane intensity on climate. *Nature* **326**: 483–485.
- Emanuel, K. 2001. Contribution of tropical cyclones to meridional heat transport by the oceans. *Journal of Geophysical Research* **106**: 14,771–14,781.
- Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436**: 686–688.
- Emanuel, K. 2001. Contribution of tropical cyclones to meridional heat transport by the oceans. *Journal of Geophysical Research* **106**: 14,771–14,781.
- Fan, D-D. and Liu, K-b. 2008. Perspectives on the linkage between typhoon activity and global warming from recent research advances in paleotempestology. *Chinese Science Bulletin* **53**: 2907–2922.
- Fedorov, A., Brierley, C., and Emanuel, K. 2010. Tropical cyclones and permanent El Niño in the early Pliocene epoch. *Nature* **463**: 1066–1070.
- Free, M., Bister, M., and Emanuel, K. 2004. Potential intensity of tropical cyclones: Comparison of results from radiosonde and reanalysis data. *Journal of Climate* **17**: 1722–1727.
- Grossmann, I. and Morgan, M.G. 2011. Tropical cyclones, climate change, and scientific uncertainty: what do we know, what does it mean, and what should be done? *Climatic Change* **108**: 543–579.
- Gualdi, S., Scoccimarro, E., and Navarra, A. 2008. Changes in tropical cyclone activity due to global warming: Results from a high-resolution coupled general circulation model. *Journal of Climate* **21**: 5204–5228.
- Hart, R.E. 2011. An inverse relationship between aggregate Northern Hemisphere tropical cyclone activity and subsequent winter climate. *Geophysical Research Letters* **38**: 10.1029/2010GL045612.
- Hart, R.E., Maue, R.N., and Watson, M.C. 2007. Estimating local memory of tropical cyclones through MPI anomaly evolution. *Monthly Weather Review* **135**: 3990–4005.
- Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., and McGuffie, K. 1998. Tropical cyclones and global climate change: A post-IPCC assessment. *Bulletin of the American Meteorological Society* **79**: 19–38.
- Jansen, M. and Ferrari, R. 2009. Impact of the latitudinal distribution of tropical cyclones on ocean heat transport. *Geophysical Research Letters* **36**: 10.1029/2008GL036796.
- Jansen, M.F., Ferrari, R., and Mooring, T.A. 2010. Seasonal versus permanent thermocline warming by tropical cyclones. *Geophysical Research Letters* **37**: 10.1029/2009GL041808.
- Klotzbach, P.J. 2006. Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophysical Research Letters* **33**: 10.1029/2006GL025881.
- Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J., and Neumann, C.J. 2010. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society* **91**: 363–376.
- Knapp, K.R., Kruk, M.C., Levinson, D.H., and Gibney, E.J. 2009. Archive compiles new resource for global tropical cyclone research. *EOS, Transactions of the American Geophysical Union* **90**: 10.1029/2009EO060002.
- Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., and Sugi, M. 2010. Tropical cyclones and climate change. *Nature Geoscience* **3**: 157–163.
- Knutson, T., Tuleya, R., and Kurihara, Y. 1998. Simulated increase of hurricane intensities in a CO₂-warmed climate. *Science* **279**: 1018–1020.
- Kossin, J.P., Knapp, K.R., Vimont, D.J., Murnane, R.J., and Harper, B.A. 2007. A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters* **34**: 10.1029/2006GL028836.
- Kuleshov, Y., Fawcett, R., Qi, L., Trewin, B., Jones, D., McBride, J., and Ramsay, H. 2010. Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean. *Journal of Geophysical Research* **115**: 10.1029/2009JD012372.
- Landsea, C.W. 2005. Hurricanes and global warming. *Nature* **438** (22 December 2005) doi:10.1038/nature04477.
- Landsea, C.W., Harper, B.A., Hoarau, K., and Knaff, J.A. 2006. Can we detect trends in extreme tropical cyclones? *Science* **313**: 252–254.
- Lane, P., Donnelly, J.P., Woodruffe, J.D., and Hawkes, A.D. 2011. A decadal-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. *Marine Geology* **287**: 14–30.
- Leipper, D.F. 1967. Observed ocean conditions and Hurricane Hilda, 1964. *Journal of the Atmospheric Sciences* **24**: 182–196.

Observations: Extreme Weather

- Lin, I., Liu, W.T., Wu, C.-C., Wong, G.T.F., Hu, C., Chen, Z., Liang, W.-D., Yang, Y., and Liu, K.-K. 2003. New evidence for enhanced primary production triggered by tropical cyclone. *Geophysical Research Letters* **30**: 10.1029/2003GL017141.
- Liu, K. and Fearn, M. 1993. Lake sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* **21**: 793–796.
- Liu, K. and Fearn, M. 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research* **54**: 238–245.
- Maloney, E.D. and Hartmann, D.L. 2000. Modulation of eastern North Pacific hurricanes by the Madden-Julian Oscillation. *Journal of Climate* **13**: 1451–1460.
- Mann, M.E., Woodruff, J.D., Donnelly, J.P., and Zhang, Z. 2009. Atlantic hurricanes and climate over the past 1,500 years. *Nature* **460**: 880–883.
- Manucharyan, G.E., Brierley, C.M., and Fedorov, A.V. 2011. Climate impacts of intermittent upper ocean mixing induced by tropical cyclones. *Journal of Geophysical Research* **116**: 10.1029/2011JC007295.
- Maue, R.N. 2011. Recent historically low global tropical cyclone activity. *Geophysical Research Letters* **38**: 10.1029/2011GL047711.
- Nelson, N.B. 1996. The wake of Hurricane Felix. *International Journal of Remote Sensing* **17**: 2893–2895.
- Nolan, D.S. and Rappin, E.D. 2008. Increased sensitivity of tropical cyclogenesis to wind shear in higher SST environments. *Geophysical Research Letters* **35**: 10.1029/2008GL034147.
- Nolan, D.S., Rappin, E.D., and Emanuel, K.A. 2007. Tropical cyclogenesis sensitivity to environmental parameters in radiative-convective equilibrium. *Quarterly Journal of the Royal Meteorological Society* **133**: 2085–2107.
- Nott, J. 2011. Tropical cyclones, global climate change and the role of Quaternary studies. *Journal of Quaternary Science* **26**: 468–473.
- Nott, J. and Forsyth, A. 2012. Punctuated global tropical cyclone activity over the past 5,000 years. *Geophysical Research Letters* **39**: 10.1029/2012GL052236.
- Pielke Jr., R.A., Gratz, J., Landsea, C.W., Collins, D., Saunders, M.A., and Musulin, R. 2008. Normalized hurricane damage in the United States: 1900–2005. *Natural Hazards Review* **9**: 29–42.
- Price, J.F. 1981. Upper ocean response to a hurricane. *Journal of Physical Oceanography* **11**: 153–175.
- Price, J.F., Morzel, J., and Niiler, P.P. 2008. Warming of SST in the cool wake of a moving hurricane. *Journal of Geophysical Research* **113**: 10.1029/2007JC004393.
- Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S., and Schlax, M.G. 2007. Daily high-resolution blended analyses for sea surface temperature. *Journal of Climate* **20**: 5473–5496.
- Rhodes, E.G., Polach, H.A., Thom, B.G., and Wilson, S.R. 1980. Age structure of Holocene coastal sediments, Gulf of Carpentaria, Australia. *Radiocarbon* **22**: 718–727.
- Romero-Vadillo, E., Zaytsev, O., and Morales-Perez, R. 2007. Tropical cyclone statistics in the northeastern Pacific. *Atmosfera* **20**: 197–213.
- Shay, L.K., Black, P.G., Hawkins, J.D., Elsberry, R.L., and Mariano, A.J. 1991. Sea surface temperature response to Hurricane Gilbert. *Nineteenth Conference on Hurricanes and Tropical Meteorology*. American Meteorological Society, Boston, Massachusetts, USA.
- Sobel, A.H. and Camargo, S.J. 2005. Influence of western North Pacific tropical cyclones on their large-scale environment. *Journal of the Atmospheric Sciences* **62**: 3396–3407.
- Soccimarro, E., Gualdi, S., Bellucci, A., Sanna, A., Fogli, P.G., Manzini, E., Vichi, M., Oddo, P., and Navarra, A. 2011. Effects of tropical cyclones on ocean heat transport in a high resolution coupled general circulation model. *Journal of Climate* **24**: 4368–4384.
- Vecchi, G.A. and Soden, B.J. 2007. Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature* **450**: 1066–1070.
- Walker, N.D., Leben, R.R., and Balasubramanian, S. 2005. Hurricane-forced upwelling and chlorophyll a enhancement within cold-core cyclones in the Gulf of Mexico. *Geophysical Research Letters* **32**: 10.1029/2005GL023716.
- Walsh, K. 2004. Tropical cyclones and climate change: unresolved issues. *Climate Research* **27**: 77–83.
- Walsh, K. and Pittock, A.B. 1998. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Climatic Change* **39**: 199–213.
- Wang, B., Yang, Y., Ding, Q.-H., Murakami, H., and Huang, F. 2010. Climate control of the global tropical storm days (1965–2008). *Geophysical Research Letters* **37**: 10.1029/2010GL042487.
- Wang, C. and Lee, S.-K. 2009. Co-variability of tropical cyclones in the North Atlantic and the eastern North Pacific. *Geophysical Research Letters* **36**: 10.1029/2009GL041469.

Climate Change Reconsidered II

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**: 1844–1846.

Woodruff, J.D., Donnelly, J.P., and Okusu, A. 2009. Exploring typhoon variability over the min-to-late Holocene: Evidence of extreme coastal flooding from Kamikoshiki, Japan. *Quaternary Science Reviews* **28**: 1774–1785.

Appendix 1

Acronyms

ACWT	Atlantic core water temperature	CASA	Carnegie-Ames-Stanford Approach
AGAGE	Advanced Global Atmospheric Gases Experiment	CBSC	Carbon-based secondary compounds
AGW	anthropogenic global warming	CCN	Cloud condensation nuclei
AMF	<i>arbuscular mycorrhizal</i> fungi	CDC	Canadian Drought Code
AMO	Atlantic Multidecadal Oscillation	CERES	Clouds and the Earth's Radiant Energy System
AMSR	Advanced Microwave Scanning Radiometer	CEVSA	Carbon Exchanges in the Vegetation-Soil-Atmosphere System
APSIM	Agricultural Production Systems Simulator	CFC	chlorofluorocarbons
AO/NAO	Arctic Oscillation/North Atlantic Oscillation	CGCM	Coupled General Circulation Models
AsA	ascorbic acid	CH₂ClI	iodocarbon chloriodomethane
ASI	aeolian sand influx	CH₃Cl	methyl chloride
ATLAS	Airborne Thermal and Land Applications Sensor	CH₄	methane
AVHRR	Advanced Very High Resolution Radiometer	CH₂I₂	diiodomethane
Ba	barium	CHD	coronary heart disease
BATS	Bermuda Atlantic Time-Series Study	CMAF	Climate Prediction Center Merged Analysis of Precipitation
BC2	Carlsbad Cavern (New Mexico)	CO₂	carbon dioxide
BCC	Buckeye Creek Cave (West Virginia)	CPR	Continuous Plankton Recorder
BioCON	Biodiversity, Carbon Dioxide, and Nitrogen Effects on Ecosystem Functioning	CPY	Climactic Pointer Years
BIOME3	Biogeochemical Model	CRII	cosmic ray-induced ionization
BP	before present	CRP1	Core Research Project 1
BSW	bog surface wetness	CRU	Climate Research Unit
Bt	<i>Bacillus thuringiensis</i>	CS₂	carbon disulfide
BYDV	barley yellow dwarf virus	CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
Ca	calcium	CWP	Current Warm Period
CAM	Crassulacean Acid Metabolism	CVD	cardiovascular disease
		CZCS	Coastal Zone Color Scanner
		DACP	Dark Ages cold period
		DDG	dry distilled grain

Climate Change Reconsidered II

DGGE	denaturing gradient gel electrophoresis	HC1	Hidden Cave (Guadalupe Mountains)
DM	dry matter	HR	heterotrophic respiration
DMS	dimethyl sulfide	HSG	hematite stained grain
DOC	dissolved organic carbon	IE	infection efficiency
ECCO	Estimating Circulation and Climate of the Ocean	IMAR	Inner Mongolia Autonomous Region
ECMWF	European Centre for Medium-Range Weather Forecasts	IMR	Indian Monsoon rainfall
EDC96	European Project for Ice Coring in Antarctica Dome C	IPCC	Intergovernmental Panel on Climate Change
EIA	Energy Information Administration (U.S.)	IPCC 2007-I	Intergovernmental Panel on Climate Change -- Group I Contribution
EF-Tu	protein synthesis elongation factor	IPCC 2007-II	Intergovernmental Panel on Climate Change -- Group II Contribution
ENSO	El Nino-Southern Oscillation	IPCC 2007-III	Intergovernmental Panel on Climate Change -- Group III Contribution
EQC	eolian quartz content	IPCC-FAR	Intergovernmental Panel on Climate Change -- First Assessment Report
FACE	Free-air CO ₂ Enrichment	IPCC-SAR	Intergovernmental Panel on Climate Change -- Second Assessment Report
FACTS	Forest Atmosphere Carbon Transfer and Storage	IPCC-TAR	Intergovernmental Panel on Climate Change -- Third Assessment Report
FB	Foxe Basin	IPCC-AR4	Intergovernmental Panel on Climate Change -- Fourth Assessment Report
GBR	Great Barrier Reef	IPCC-AR5	Intergovernmental Panel on Climate Change -- Fifth Assessment Report
GCM	General Circulation Models	IRD	ice rafted debris
GCR	galactic cosmic rays	ISCCP	International Satellite Cloud Climatology Project
GCTE	Global Change and Terrestrial Ecosystems	ISM	Indian Summer Monsoon
GDP	Gross Domestic Product	ITCZ	Intertropical Convergence Zone
GEI	Glacier Expansion Index	ITS2	Internal Transcribed Spacer Region 2
GHG	green house gas(es)	IUCN	International Union for Conservation of Nature
GIMMS	Global Inventory Modeling and Mapping Studies	LBM	larch budmoth
GIS	Greenland Ice Sheet	LCA	low cloud amount
GISS	Goddard Institute of Space Studies	LCLU	land cover and land use
GLO-PEM	Global Production Efficiency Model	LGM	Last Glacial Maximum
gNDVI	Normalized Difference Vegetation Index over the Growing Season	LIA	Little Ice Age
GPCP	Global Precipitation Climatology Project	LST	land surface temperature
gr	gram(s)	LTM	long-term mean standardization
GRACE	Gravity Recovery and Climate Experiment	m	meter
GREET	Greenhouse gases Regulated Emissions and Energy Use in Transportation	Ma BP	million years before present
GSH	glutathione	MAAT	mean annual air temperature
GSL	global sea level		

Appendix 1: Acronyms

MBP	mass balance potential	Ps	solid precipitation
MDR	main development region	RACM	Regional Atmospheric Climate Model
ME	surface melt	RCC	rapid climate change
MJ	mega joule	RCS	regional curve standardization
MS	methanesulfonate	Rd	ratio of diffuse
MSA	methanesulfonic Acid	Rda	area-based dark respiration
MTBE	methyl tertiary butyl ether	Rdm	mass-based dark respiration
MWP	Medieval Warm Period	rDNA	ribosomal deoxyribonucleic acid
MXD	maximum latewood density	Rg	solar irradiance
MY	multiyear	ROS	reactive oxygen species
N₂O	nitrous oxide	RWP	Roman Warm Period
NABE	North Atlantic Bloom Experiment	SACC	Screen-Aided CO ₂ Control
NADW	North Atlantic deep water	SAT	surface air temperature
NAM	Northern Annular Mode	SB	Southern Beaufort Sea
NAO	North Atlantic Oscillation	SCC	Swiss Canopy Crane Project
NAS	National Academy of Sciences	SCPDSI	Self-Calibrating Palmer Drought Severity Index
NDVI	Normalized Difference Vegetation Index	SeaWiFS	Sea-Viewing Wide Field-Of-View Sensor
NEP	net ecosystem production	SEPP	Science & Environmental Policy Project
NIPCC	Nongovernmental International Panel on Climate Change	SFP	South Fork Payette
NMHC	non-methane hydrocarbon	SMB	surface mass balance
NPP	net primary production	SMR	snowmelt runoff
nss-SO₄²⁻	non-sea-salt sulfate	SODA	Simple Ocean Data Assimilation
NWS	National Weather Service	SOM	soil organic matter
O₃	ozone	SPAR	Soil-Plant-Atmosphere-Research Facility (Mississippi)
OCS	carbonyl sulfide	SPCZ	South Pacific Convergence Zone
OLR	outgoing longwave radiation	SPM	Summaries for Policymakers
OM	organic matter	SPS	sucrose-phosphate synthase
OTC	open-top chambers	SSM/I	Special Sensor Microwave Imager
P	precipitation	SSMR	Scanning Multichannel Microwave Radiometer
PAL	Pathfinder AVHRR [Advanced Very High Resolution Radiometer] Land	SN/SSN	sunspot number
PDO	Pacific Decadal Oscillation	SST	sea surface temperatures
PDSI	Palmer Drought Severity Index	STF	subtropical front
PF	polar front	SU	surface sublimation
PGR	post-glacial rebound	SWE	snow water equivalent
PI	potential intensity	SWF	shortwave flux
PIZ	perennial ice zone		
ppb	parts per billion		
ppm	parts per million		

Climate Change Reconsidered II

SWM	Southwest Monsoon	TSI	total solar irradiance
TBE	tick-borne encephalitis	UHI	urban heat island
TBEV	tick-borne encephalitis virus	UNEP	United Nations Environment Program
TC	tropical cyclones	UV	ultraviolet
Tmax	maximum temperature	VS	vertical wind shear
Tmin	minimum temperature	WAIS	West Antarctic Ice Sheet
TMI	Tropical Rainfall Measuring Mission Microwave Imager	WH	Western Hudson Bay
T_{opt}	optimum temperature	WMO	World Meteorological Organization
TP	Tibetan Plateau	WNP	Western North Pacific
TRFO	tropical rainforest	WSC	water-soluble carbohydrate
TRMM	Tropical Rainfall Measuring Mission	WT	wild type
		WUE	water use efficiency

Appendix 2

Authors, Contributors, and Reviewers

Lead Authors/Editors

Idso, Craig D.

Center for the Study of Carbon Dioxide and Global Change
USA

Carter, Robert M.

Emeritus Fellow
Institute of Public Affairs
Australia

Singer, S. Fred

Science and Environmental Policy Project
USA

Chapter Lead Authors

Ball, Timothy

Research Fellow
Frontier Centre for Public Policy
Canada

Carter, Robert M.

Emeritus Fellow
Institute of Public Affairs
Australia

Easterbrook, Don J.

Professor Emeritus of Geology
Western Washington University
USA

Idso, Craig D.

Center for the Study of Carbon Dioxide and Global Change
USA

Idso, Sherwood

Center for the Study of Carbon Dioxide and Global Change
USA

Khandekar, Madhav

Former Research Scientist
Environment Canada
Canada

Kininmonth, William

Science Advisor
Australian Climate Science Coalition
Australia

de Lange, Willem

Science and Engineering Department
The University of Waikato
New Zealand

Lüning, Sebastian

Geologist and Author
Germany

Lupo, Anthony

School of Natural Resources
University of Missouri
USA

Ollier, Cliff

School of Earth and Geographical Sciences
University of Western Australia
Australia

Soon, Willie

Independent Scientist
USA

Contributing Authors

Armstrong, J. Scott

Wharton School
University of Pennsylvania
USA

Climate Change Reconsidered II

D'Aleo, Joseph

Co-chief Meteorologist
Weatherbell Analytic
USA

Easterbrook, Don J.

Professor Emeritus of Geology
Western Washington University
USA

Green, Kesten

International Graduate School of Business
University of South Australia
Australia

McKittrick, Ross

Department of Economics
University of Guelph
Canada

Ollier, Cliff

School of Earth and Geographical Sciences
University of Western Australia
Australia

Segalstad, Tom

Resource and Environmental Geology
University of Oslo
Norway

Singer, S. Fred

Science and Environmental Policy Project
USA

Spencer, Roy

Principal Research Scientist
University of Alabama in Huntsville
USA

Chapter Reviewers**Abdussamatov, Habibullo**

Space Research Laboratory
Pulkovo Observatory
Russian Academy of Sciences
Russia

Bastardi, Joe

Co-chief Meteorologist
Weatherbell Analytic
USA

Battaglia, Franco

Professor of Environmental Chemistry
University of Modena
Italy

Bowen, David Q.

Professor Emeritus, School of Earth & Ocean Sciences
Cardiff University
UK

Clark, Roy

Ventura Photonics
USA

Courtillot, Vincent

Professor Emeritus
University Paris Diderot and
Institut de Physique du Globe
France

Essex, Christopher

Department of Applied Mathematics
University of Western Ontario
Canada

Evans, David

Independent Scientist, Sciencespeak.com, and Former
Carbon Modeller
Australian Greenhouse Office
Australia

Floderus, Sören

Consultant
SF Bureau
Denmark

Franks, Stewart W.

School of Engineering
University of Newcastle
Australia

Friis-Christensen, Eigil

Professor Emeritus
National Space Institute
Technical University of Denmark
Denmark

Goldberg, Fred

Swedish Polar Institute
Sweden

Gould, Laurence

Professor of Physics
University of Hartford
USA

Appendix 2: Authors, Contributors, and Reviewers

Gray, William

Emeritus Professor of Atmospheric Science
Colorado State University
USA

Gray, Vincent Richard

Climate Consultant
New Zealand

Hayden, Howard

Professor of Physics Emeritus
University of Connecticut
USA

Hovland, Martin

Professor Emeritus
Centre for Geobiology
University of Bergen
Norway

Kärner, Olavi

Atmospheric Sensing Group
Tartu Observatory
Estonia

O'Brien, James

Department of Earth, Ocean, and Atmospheric Science
Florida State University
USA

Paltridge, Garth

Emeritus Professor and Honorary Research Fellow
University of Tasmania
Australia

Rapp, Donald

Senior Research Scientist and Division Chief Technologist
(retired)
Jet Propulsion Lab
USA

Ribbing, Carl

Department of Engineering Sciences, Solid State Physics
Uppsala University
Sweden

Scafetta, Nicola

Department of Physics
Duke University
USA

Shade, John

Industrial Statistics Consultant
UK

Sharp, Gary

Independent Consultant
Center for Climate/
Ocean Resources Study
USA

Solheim, Jan-Erik

Professor emeritus
Department of Physics and Technology
University of Tromsø
Norway

Uriarte Cantolla, Antón

Sociedad de Ciencias Naturales Aranzadi
Spain

Weber, Gerd-Rainer

Independent Meteorologist
Germany

Editors**Karnick, S.T.**

The Heartland Institute
USA

Bast, Diane Carol

The Heartland Institute
USA