

Climate Change Reconsidered II

Physical Science

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Reviews of *Climate Change Reconsidered II: Physical Science*

"I fully support the efforts of the Nongovernmental International Panel on Climate Change (NIPCC) and publication of its latest report, *Climate Change Reconsidered II: Physical Science*, to help the general public to understand the reality of global climate change."

Kumar Raina, Former Deputy Director General
Geological Survey of India

"*Climate Change Reconsidered II* fulfills an important role in countering the IPCC part by part, highlighting crucial things they ignore such as the Little Ice Age and the recovery (warming) which began in 1800–1850. Superimposed on that recovery, there is a prominent multi-decadal oscillation. These can explain much of climate change from 1800, including the fact that the warming has halted from 2000, phenomena the IPCC reports do not properly cover. In contrast to the IPCC, which often ignores evidence of past changes, the authors of the NIPCC report recognize that climatology requires studying past changes to infer future changes."

Syun-Ichi Akasofu
Founding Director & Professor of Physics Emeritus
International Arctic Research Center, University of Alaska Fairbanks

"The work of the NIPCC to present the evidence for natural climate warming and climate change is an essential counter-balance to the biased reporting of the IPCC. They have brought to focus a range of peer-reviewed publications showing that natural forces have in the past and continue today to dominate the climate signal."

Ian Clark, Department of Earth Sciences
University of Ottawa, Canada

"The CCR-II report correctly explains that most of the reports on global warming and its impacts on sea-level rise, ice melts, glacial retreats, impact on crop production, extreme weather events, rainfall changes, etc. have not properly considered factors such as physical impacts of human activities, natural variability in climate, lopsided models used in the prediction of production estimates, etc. There is a need to look into these phenomena at local and regional scales before sensationalization of global warming-related studies."

S. Jeevananda Reddy, Former Chief Technical Advisor
United Nations World Meteorological Organization

"Library shelves are cluttered with books on global warming. The problem is identifying which ones are worth reading. The NIPCC's CCR-II report is one of these. Its coverage of the topic is comprehensive without being superficial. It sorts through conflicting claims made by scientists and highlights mounting evidence that climate sensitivity to carbon dioxide increase is lower than climate models have until now assumed."

Chris de Freitas, School of Environment
The University of Auckland, New Zealand

"Rather than coming from a pre-determined politicized position that is typical of the IPCC, the NIPCC constrains itself to the scientific process so as to provide objective information. If we (scientists) are honest, we understand that the study of atmospheric processes/dynamics is in its infancy. Consequently, the work of the NIPCC and its most recent report is very important."

Bruce Borders, Professor of Forest Biometrics
Warnell School of Forestry and Natural Resources, University of Georgia

"I support [the work of the NIPCC] because I am convinced that the whole field of climate and climate change urgently needs an open debate between several 'schools of thought,' in science as well as other disciplines, many of which jumped on the IPCC bandwagon far too readily. Climate, and even more so impacts and responses, are far too complex and important to be left to an official body like the IPCC."

Sonja A. Boehmer-Christiansen
Reader Emeritus, Department of Geography, Hull University
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Physical Science

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Foreword

The Heartland Institute is pleased to partner once again with the Center for the Study of Carbon Dioxide and Global Change and the Science and Environmental Policy Project to produce an authoritative and independent assessment of the latest science concerning the causes and consequences of climate change.

Many scientists, policymakers, and engaged citizens are concerned over the possibility that man-made greenhouse gas emissions, in particular carbon dioxide (CO₂), may be causing dangerous climate change. A primary reason for this public alarm is a series of reports issued by the United Nations' Intergovernmental Panel on Climate Change (IPCC). The IPCC claims to know, with apparent rising certainty over time, that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007, p. 10). Is this conclusion based on sound science?

Climate change is a controversial topic because it is interdisciplinary: scientists and experts in widely divergent fields of study can rightfully weigh in on the debate with their insights and informed opinions. A historian of the global warming debate recently observed that "economists should be in a better position than others to make their own assessment of the science because much of it is about statistics and modeling" (Darwall, 2013, p. 239). He quotes Canadian economist Ross McKittrick as saying "the typical economist has way more training in data analysis than a typical climatologist," and "once they start reading climate papers they start spotting errors all over the place." Of course, economists also have their own blind spots.

What is necessary, and too seldom takes place, is a respectful debate on the causes and consequences of

climate change in which ideas and theories rise or fall on their merits rather than their pedigree or influence on public policy. A technique frequently used in industry, government, and law when dealing with complex or controversial matters is to deploy competing Green and Red Teams to pursue alternative approaches (e.g., Sandoz, 2001; Nemeth *et al.*, 2001). A Red Team provides a kind of "defense counsel" to verify and counter arguments mounted by the initial Green Team (the "prosecution") as well as discover and present alternatives the Green Team may have overlooked.

For many years, the Green Team of the IPCC has dominated the global debate over climate change. In 2003, however, at a meeting in Milan, a Red Team started to emerge composed of independent scientists drawn from universities and private institutions around the world. Since 2008 that team, the Nongovernmental International Panel on Climate Change (NIPCC), has been independently evaluating the impacts of rising atmospheric CO₂ concentrations on Earth's biosphere and evaluating forecasts of future climate effects.

NIPCC: A Brief History

The Nongovernmental International Panel on Climate Change, or NIPCC, is an international panel of scientists and scholars who came together to understand the causes and consequences of climate change. NIPCC has no formal attachment to or sponsorship from any government or governmental agency. It is wholly independent of political pressures and influences and therefore is not predisposed to produce politically motivated conclusions or policy recommendations.

NIPCC seeks to objectively analyze and interpret data and facts without conforming to any specific agenda. This organizational structure and purpose

stand in contrast to those of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which *is* government-sponsored, politically motivated, and predisposed to believing that climate change is a problem in need of a U.N. solution.

NIPCC traces its beginnings to an informal meeting held in Milan, Italy in 2003 organized by Dr. S. Fred Singer and the Science and Environmental Policy Project (SEPP). The purpose was to produce an independent evaluation of the available scientific evidence on the subject of carbon dioxide-induced global warming in anticipation of the release of the IPCC's Fourth Assessment Report. NIPCC scientists concluded the IPCC was biased with respect to making future projections of climate change, discerning a significant human-induced influence on current and past climatic trends, and evaluating the impacts of potential carbon dioxide-induced environmental changes on Earth's biosphere.

To highlight such deficiencies in the IPCC's report, in 2008 SEPP partnered with The Heartland Institute to produce *Nature, Not Human Activity, Rules the Climate*, a summary of research for policymakers that has been widely distributed and translated into six languages. In 2009, Craig Idso and the Center for the Study of Carbon Dioxide and Global Change joined the original two sponsors to help produce *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*, the first comprehensive alternative to the alarmist reports of the IPCC.

In 2010, a Web site (www.nipccreport.org) was created to highlight scientific studies NIPCC scientists believed would likely be downplayed or ignored by the IPCC during preparation of its next assessment report. In 2011, the three sponsoring organizations along with a new co-author, Australian marine geologist Robert M. Carter, produced *Climate Change Reconsidered: The 2011 Interim Report of the Nongovernmental International Panel on Climate Change (NIPCC)*, a review and analysis of new research released since the 2009 report or overlooked by the authors of that report.

In 2013, the Information Center for Global Change Studies, a division of the Chinese Academy of Sciences, translated and published an abridged edition of the 2009 and 2011 NIPCC reports in a single volume. On June 15, the Chinese Academy of Sciences organized a NIPCC Workshop in Beijing to allow the NIPCC principal authors to present

summaries of their conclusions.

For all its reports, NIPCC has worked with leading thinkers in the fields of statistics, physics, economics, geology, climatology, and biology. It has avoided the appeals to authority, assumptions, and circumstantial evidence that characterize the reports of the IPCC and other partisans in this debate. The result is a contribution to the debate that reveals some inconvenient truths based squarely on the best available research on climate.

CCR II: Physical Science

Climate Change Reconsidered II: Physical Science is NIPCC's latest report. Lead authors Craig D. Idso, Robert M. Carter, and S. Fred Singer have worked with a team of nearly 50 scientists to produce a report that is comprehensive, objective, and faithful to the scientific method. Despite its heft, it is only the first of two volumes that together mirror and rebut the IPCC's Working Group 1 and Working Group 2 reports. The second volume of *CCR II*, planned for release in 2014, will address impacts, adaptation, and vulnerabilities.

Like the IPCC's reports, NIPCC's reports cite thousands of articles appearing in peer-reviewed science journals relevant to the subject of human-induced climate change. NIPCC presents its findings in seven chapters:

- Global Climate Models
- Forcings and Feedbacks
- Solar Forcing of Climate
- Observations: Temperature Records
- Observations: The Cryosphere
- Observations: The Hydrosphere and Oceans
- Observations: Extreme Weather

In keeping with its Red Team mission, NIPCC authors paid special attention to contributions that were either overlooked by the IPCC or that contain data, discussion, or implications arguing against the IPCC's claim that dangerous global warming is resulting, or will result, from human-related greenhouse gas emissions. The Executive Summary beginning on page 1 summarizes NIPCC's principal findings. Most notably, its authors say the IPCC has exaggerated the amount of warming they predict will occur in response to projected increases in atmospheric CO₂. Any such warming that may occur is likely to be modest and will not pose a dangerous

Foreword

threat to the global environment or to human well-being.

Policy Implications

Few scientists deny that human activities can have an effect on local climate or that the sum of such local effects could hypothetically rise to the level of an observable global signal. The key questions to be answered, however, are whether the human global signal is large enough to be properly measured and if it is, does it represent, or is it likely to become, a dangerous change outside the range of natural variability?

NIPCC's conclusion, drawn from its extensive review of the scientific evidence, is that the greenhouse gas-induced global climate signal is so small as to be embedded within the background variability of the natural climate system and is not dangerous. At the same time, global temperature change is occurring, as it always naturally does. A phase of temperature stasis or cooling has succeeded the mild twentieth century warming. It is certain that similar natural climate changes will continue to occur.

In the face of such facts, the most prudent climate policy is to prepare for and adapt to natural climate events and the threats they pose to society regardless of their origin. Adaptive planning for future hazardous climate events and change should be tailored to provide reasonable responses to their known rates, magnitudes, and risks. Once in place, these plans will provide an adequate response to any human-caused change that may or may not emerge.

Policymakers should resist pressure from lobby groups to silence those who question the authority of the IPCC as the sole gatekeeper and voice speaking in behalf of "climate science." *Climate Change Reconsidered II: Physical Science* reveals a scientific

community deeply uncertain about the reliability of the IPCC's computer models, its postulates, and its interpretation of circumstantial evidence. This criticism doesn't come from a "fringe" group of the climate science community: It is stated plainly and repeated in thousands of articles in the peer-reviewed literature.

The distinguished British biologist Conrad Waddington wrote in 1941,

It is ... important that scientists must be ready for their pet theories to turn out to be wrong. Science as a whole certainly cannot allow its judgment about facts to be distorted by ideas of what ought to be true, or what one may hope to be true (Waddington, 1941).

This prescient statement merits careful examination by those who continue to assert the fashionable belief, in the face of strong empirical evidence to the contrary, that human CO₂ emissions are going to cause dangerous global warming.

Acknowledgements

As we did in the forewords of previous volumes in the *Climate Change Reconsidered* series, we extend our thanks and appreciation to the many scientists and other experts who helped write this report and its precursors, and to those who conducted the original research that is summarized and cited.

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Preface

This report is the result of collaboration among three organizations: Center for the Study of Carbon Dioxide and Global Change, Science & Environmental Policy Project, and The Heartland Institute. Three lead authors -- Craig D. Idso, Robert M. Carter, and S. Fred Singer – assembled and worked closely with nearly 50 chapter lead authors, contributors, and reviewers from 15 countries. This volume was subjected to the common standards of peer-review. Reviewers who agreed to be identified are listed on the title page.

The material presented in this volume builds on three prior NIPCC reports, *Nature, Not Human Activity, Controls the Climate* (Singer, 2008), *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)* (Idso and Singer, 2009), and *Climate Change Reconsidered: The 2011 Interim Report of the Nongovernmental International Panel on Climate Change* (Idso, Carter, and Singer, 2011).

Like its predecessor reports, this volume provides the scientific balance that is missing from the overly alarmist reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which are highly selective in their review of climate science and controversial with regard to their projections of future climate change. Although the IPCC claims to be unbiased and to have based its assessment on the best available science, we have found this to not be the case. In many instances conclusions have been seriously exaggerated, relevant facts have been distorted, and key scientific studies have been ignored.

A careful reading of the chapters below reveals *thousands* of peer-reviewed scientific journal articles that do not support, and indeed often contradict, the

IPCC's alarmist perspective on climate change. This is not an exercise in "cherry picking": There are simply too many articles by too many prominent scientists, reporting too much real-world data and not merely opinions. Either the IPCC purposely ignores these articles because they run counter to their predetermined thesis that man is causing a climatic crisis, or the IPCC's authors are incompetent and failed to conduct a proper scientific investigation. Either way, the IPCC is misleading the scientific community, policymakers, and the general public by telling only half the story about the science of climate change.

If the IPCC truly considered and acknowledged *all* pertinent science in its assessment reports, there would be no need for a NIPCC. Until such time as the IPCC changes its ways (or is dissolved), NIPCC will continue to inject balance into the scientific debate by finding and reporting the scientific research that the IPCC overlooks. Much of it deals with natural climate processes or variability, weaknesses in climate models and data sets used to measure temperatures or forecast future climate conditions, or with data that raise serious scientific questions about the IPCC's attribution of climate change to human greenhouse gas emissions. Our sole goal in presenting this information is to enable fellow scientists, elected officials, educators, and the general public to make up their own minds about what the science says, to *understand* climate change rather than simply *believe* in it.

Each of the seven chapters in this volume begins with a list of key findings that contradict those of the IPCC. These findings are then discussed in detail using in-depth reviews and analyses of literally thousands of scientific papers. Full citations to the

work reviewed are presented at the end of each section. Some of the material is repeated from the 2011 Interim Report and from the earlier 2009 Report, though material from the oldest report is highly abridged and mostly consists of supporting references.

NIPCC scientists have worked hard to remain true to the facts in their representations of the cited studies. Quotations from the original authors are frequently used in discussing their findings and the significance of their work, while editorial commentary in each chapter section is generally limited to an initial introduction and/or conclusion.

Not every scientist whose work we cite is skeptical of the IPCC positions. In fact, there may be many among the thousands we quote who fully embrace the IPCC's claims and projections who may be bothered to see their work quoted in a book written by "skeptics." In scientific research and writing, this is not unusual and is even to be expected. Climate change is a complex topic spanning many disciplines. Climatology as a field is young and new discoveries are being made seemingly every day that reveal how little we actually know about how the climate works. So an expert in one field may not understand or follow the latest developments in another field, and depends on an organization like the IPCC to report accurately and truthfully on the overall picture of the human impact on climate. One important finding from our work is that the IPCC has abused that trust and misled countless scientists and policymakers.

A related but different matter is that some of the authors whose papers we cite may not agree with our

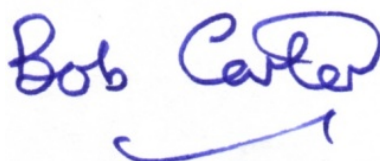
interpretation of their work. We are not infallible, so it may be the case that honest mistakes were made. More common, though, are instances noted in the text where we point out that an author's actual findings disagree with the opinions he or she express in introductions and conclusions. By providing ample quotations from the actual findings, we think readers can make up their own minds about who is right.

Finally, we acknowledge that none of NIPCC's scientists knows the truth of all matters related to the global change debate, nor can we say with certainty that this volume doesn't contain a mistake or two in our interpretations of the available evidence. Understanding climate change involves research in many branches of science across a multitude of spatial and temporal scales. We lay no claim to any special source of knowledge that is not available to anyone else on the planet, nor do we pretend to possess superlative powers of discernment. We just look at the data like everyone else does (or should) and then do our level best to decide what they mean. The fruits of that labor are contained in the NIPCC reports we produce, including the present volume.

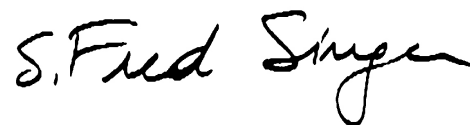
We wish to thank all those who participated in the writing, reviewing, editing, and proofing of this volume. Our sincere hope is that this report will mark a return to a more balanced and factually-driven analysis of an issue that is in desperate need of much fuller and open discussion, and that it will help policymakers and politicians make rational decisions on climate and energy policy based on *all* the pertinent science, not just the one-sided narrative produced by the IPCC.



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Executive Summary

This report is produced by the Nongovernmental International Panel on Climate Change (NIPCC), a joint project of three organizations: Center for the Study of Carbon Dioxide and Global Change, Science & Environmental Policy Project, and The Heartland Institute. Three lead authors – Craig D. Idso, Robert M. Carter, and S. Fred Singer – assembled and worked closely with nearly 50 chapter lead authors, contributors, and reviewers from 15 countries. This volume was subjected to the common standards of peer-review.

This work provides the scientific balance that is missing from the overly alarmist reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which are highly selective in their review of climate science and controversial with regard to their projections of future climate change. Although the IPCC claims to be unbiased and to have based its assessment on the best available science, we have found this to not be the case. In many instances conclusions have been seriously exaggerated, relevant facts have been distorted, and key scientific studies have been ignored.

In keeping with its “Red Team” mission, NIPCC authors paid special attention to contributions that were either overlooked by the IPCC or that contain data, discussion, or implications arguing against the IPCC's claim that dangerous global warming is resulting, or will result, from human-related greenhouse gas emissions. Most notably, its authors say the IPCC has exaggerated the amount of warming they predict to occur in response to future increases in atmospheric CO₂. Any warming that may occur is likely to be modest and cause no net harm to the global environment or to human well-being.

Key Findings by Chapter

Chapter 1. Global Climate Models and Their Limitations

- Properties inherent in models make dynamic predictability impossible. Without dynamic predictability, other techniques must be used to simulate climate. Such techniques introduce biases of varying magnitude into model projections.
- To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes involved in determining climate, but also all important chemical and biological processes that influence climate over long time periods. Several of these important processes are either missing or inadequately represented in today's state-of-the-art climate models.
- Limitations in computing power frequently result in the inability of models to resolve important climate processes. Low-resolution models fail to capture many important phenomena of regional and lesser scales, such as clouds; downscaling to higher-resolution models introduces boundary interactions that can contaminate the modelling area and propagate error.
- The magnitude of the range of projected responses to a doubling of atmospheric CO₂ by itself establishes that large errors and limitations in the models remain to be corrected.
- Many GCMs fail to account properly for certain “multiplier effects” that may significantly amplify the initial impacts of various biospheric processes.

For example, although the absolute variations associated with some solar-related phenomena are rather small, Several multiplier effects may significantly amplify the initial perturbation.

- Major imperfections in the models prevent proper simulation of important elements of the climate system, including pressure, wind, clouds, temperature, precipitation, ocean currents, sea ice, permafrost, etc. Large differences between model predictions and observations frequently exist when comparing these elements or features. In some cases computer models fail to simulate even the correct sign of the observed parameters.
- Although some improvements have been noted in performance between the CMIP3 set of models used in AR4 and the newer CMIP5 models utilized in AR5, many researchers report finding little or no improvement in the CMIP5 model output for several important parameters and features of Earth's climate.

Chapter 2. Forcings and Feedbacks

- Research published in peer-reviewed science journals indicates the model-derived temperature sensitivity of Earth accepted by the IPCC is too large. Negative feedbacks in the climate system reduce that sensitivity to values an order of magnitude smaller.
- Establishing the historic phase relationship between atmospheric carbon dioxide and temperature is a necessary step toward understanding the physical relationship between CO₂ forcing and climate change. When such analyses are conducted, changes in CO₂ are frequently seen to *lag* changes in temperature by several hundred years.
- Many studies reveal a large *uncoupling* of temperature and CO₂ throughout portions of the historical record. Such findings contradict the IPCC's theory that changes in atmospheric CO₂ drive changes in temperature.
- Atmospheric methane observations over the past two decades reside far below the values projected by the IPCC in each of the four *Assessment*

Reports it has released to date. The IPCC's temperature projections, which incorporate this inflated influence, should be revised downward to account for this discrepancy.

- Because agriculture accounts for almost half of nitrous oxide (N₂O) emissions in some countries, there is concern that enhanced plant growth due to CO₂ enrichment might increase the amount and warming effect of this greenhouse gas. But field research shows N₂O emissions will likely fall as CO₂ concentrations and temperatures rise, indicating this is actually another negative climate feedback.
- The IPCC has concluded "the net radiative feedback due to all cloud types is likely positive" (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, several studies indicate the net global effect of cloud feedbacks is a cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.
- The IPCC likely underestimates the total cooling effect of aerosols. Studies have found their radiative effect is comparable to or larger than the temperature forcing caused by all the increase in greenhouse gas concentrations recorded since preindustrial times.
- Higher temperatures are known to increase emissions of dimethyl sulfide (DMS) from the world's oceans, which increases the albedo of marine stratus clouds, which has a cooling effect. The IPCC characterizes this chain of events as "a rather weak aerosol-climate feedback at the global scale" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012), but many studies suggest otherwise.
- Several other important negative forcings and feedbacks exist in nature, about which little is known or acknowledged by the IPCC. Such forcings and feedbacks have been shown by multiple scientific studies to significantly influence Earth's climate to a degree comparable to that of projected anthropogenic-induced global warming.

Executive Summary

- The IPCC claims a positive feedback exists between climate and the carbon cycle on century to millennial time scales such that a warming climate will result in a loss of carbon storage. There is no empirical evidence to support such an assertion. Just the opposite appears to be the case, as global carbon uptake doubled over the past half-century.

Chapter 3. Solar Forcing of Climate

- Evidence is accruing that changes in Earth's surface temperature are largely driven by variations in solar activity. Examples of solar-controlled climate change epochs include the Medieval Warm Period, Little Ice Age and Early Twentieth Century (1910–1940) Warm Period.
- The Sun may have contributed as much as 66% of the observed twentieth century warming, and perhaps more.
- Strong empirical correlations have been reported from all around the world between solar variability and climate indices including temperature, precipitation, droughts, floods, streamflow, and monsoons.
- IPCC models do not incorporate important solar factors such as fluctuations in magnetic intensity and overestimate the role of human-related CO₂ forcing.
- The IPCC fails to consider the importance of the demonstrated empirical relationship between solar activity, the ingress of galactic cosmic rays, and the formation of low clouds.
- The respective importance of the Sun and CO₂ in forcing Earth climate remains unresolved; current climate models fail to account for a plethora of known Sun-climate connections.
- The recently quiet Sun and extrapolation of solar cycle patterns into the future suggest a planetary cooling may occur over the next few decades.

Chapter 4. Observations: Temperature Records

- The warming of the late-twentieth-century as well as the cessation of warming that occurred since 1998 fall well within the range of natural climate variability.
- Surface-based temperature histories of the globe contain a significant warming bias introduced by insufficient corrections for the non-greenhouse-gas-induced urban heat island effect. Filtering out urbanization and related land-use effects in the temperature record is a complicated task, and there is solid evidence the methods currently used are inadequate.
- Although all greenhouse models show an increasing warming trend with altitude, peaking around 10 km at roughly two times the surface value, the temperature data from balloons give the opposite result: no increasing warming, but rather a slight cooling with altitude in the tropical zone.
- The IPCC claim of robust evidence of amplified CO₂-induced warming in Earth's polar regions is false, having been invalidated time and again by real-world data.
- Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration, revealing the true inability of carbon dioxide to drive climate change throughout the Holocene. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades and centuries even though the atmosphere's CO₂ concentration remained at values approximately 30% lower than those of today.
- An enormous body of literature clearly demonstrates the IPCC's assessment of the Medieval Climate Anomaly (MCA) is incorrect. The degree of warming and climatic influence during the MCA indeed varied from region to region, and hence its consequences were manifested in a variety of different ways. But that it occurred and was a global phenomenon is certain.

- 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. However, this is generally not what observational data reveal to be the case. In fact, in nearly all historical records it is seen that 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).
- 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.

Chapter 5. Observations: The Cryosphere

- 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.
- 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.

- 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.

Chapter 6. Observations: The Hydrosphere and Oceans

The Hydrosphere

- Little evidence exists for an overall increase in global precipitation during the twentieth century independent of natural multidecadal climate rhythmicity.
- Monsoon precipitation did not become more variable or intense during late twentieth century warming; instead, precipitation responded mostly to variations in solar activity.
- South American and Asian monsoons were more active during the cold Little Ice Age and less active during the Medieval Warm Period. Neither global nor local changes in streamflow have been linked to CO₂ emissions.
- The relationship between drought and global warming is weak, since severe droughts occurred during both the Medieval Warm Period and the Little Ice Age.

Oceans

- Knowledge of local sea-level change is vital for coastal management; such change occurs at widely variable rates around the world, typically between about +5 and -5 mm/year.
- Global (eustatic) sea level, knowledge of which has only limited use for coastal management, rose at an average rate of between 1 and 2 mm/year over the past century.
- Satellite altimeter studies of sea-level change indicate rates of global rise since 1993 of over 3 mm/year, but complexities of processing and the infancy of the method precludes viewing this result as secure.
- Rates of global sea-level change vary in decadal and multidecadal ways and show neither recent acceleration nor any simple relationship with increasing CO₂ emissions.
- Pacific coral atolls are not being drowned by extra sea-level rise; rather, atoll shorelines are affected by direct weather and infrequent high tide events, ENSO sea level variations, and impacts of increasing human populations.
- Extra sea-level rise due to heat expansion (thermohaline rise) is also unlikely given that the Argo buoy network shows no significant ocean warming over the past nine years.
- Though the range of natural variation has yet to be fully described, evidence is lacking for any recent changes in global ocean circulation that lie outside natural variation or were forced by human CO₂ emissions.

Chapter 7. Observations: Extreme Weather

- 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.

1

Global Climate Models and Their Limitations

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Key Findings

The IPCC places great confidence in the ability of global climate models (GCMs) to simulate future climate and attribute observed climate change to anthropogenic emissions of greenhouse gases. They claim the “development of climate models has resulted in more realism in the representation of many quantities and aspects of the climate system,” adding, “it is extremely likely that human activities have caused more than half of the observed increase in global average surface temperature since the 1950s” (p. 9 and 10 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012).

This chapter begins with a brief review of the inner workings and limitations of climate models. Climate models are important tools utilized to advance our understanding of current and past climate. They also provide qualitative and quantitative information about potential future climate. But in spite of all their sophistication, they remain merely models. They represent simulations of the real world, constrained by their ability to correctly capture and portray each of the important processes that operate to affect climate. Notwithstanding their complexities, the models remain deficient in many aspects of their portrayal of the climate, which reduces their ability to provide reliable simulations of future climate.

Confidence in a model is further based on the careful evaluation of its performance, in which model output is compared against actual observations. A large portion of this chapter, therefore, is devoted to the evaluation of climate models against real-world climate and other biospheric data. That evaluation, summarized in the findings of numerous peer-reviewed scientific papers described in the different subsections of this chapter, reveals the IPCC is overestimating the ability of current state-of-the-art GCMs to accurately simulate both past and future climate. The IPCC’s stated confidence in the models, as presented at the beginning of this chapter, is likely exaggerated. The many and varied model deficiencies discussed in this chapter indicate much work remains to be done before model simulations can be treated with the level of confidence ascribed to them by the IPCC.

The following points summarize the main findings of this chapter:

- Properties inherent in models make dynamic predictability impossible. Without dynamic predictability, other techniques must be used to simulate climate. Such techniques introduce biases of varying magnitude into model projections.
- To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes involved in determining climate, but also all important chemical and biological processes that influence climate over long time periods. Several of these processes are either missing or inadequately represented in today’s state-of-the-art climate models.
- Limitations in computing power frequently result in the inability of models to resolve important climate processes. Low-resolution models fail to capture many important phenomena of regional and lesser scales, such as clouds; downscaling to higher-resolution models introduces boundary interactions that can contaminate the modelling area and propagate error.
- The magnitude of the range of projected responses to a doubling of atmospheric CO₂ by itself establishes that large errors and limitations in the models remain to be corrected.
- Many GCMs fail to account properly for certain “multiplier effects” that may significantly amplify the initial impacts of various biospheric processes. For example, although the absolute variations associated with some solar-related phenomena are rather small, several multiplier effects may significantly amplify the initial perturbation.
- Major imperfections in the models prevent proper simulation of important elements of the climate system, including pressure, wind, clouds, temperature, precipitation, ocean currents, sea ice, permafrost, etc. Large differences between model predictions and observations frequently exist when comparing these elements or features. In some cases computer models fail to simulate even the correct sign of the observed parameters.
- Although some improvements have been noted in performance between the CMIP3 set of models used in AR4 and the newer CMIP5 models utilized in AR5, many researchers report finding little or no improvement in the CMIP5 model output for several important parameters and features of Earth’s climate.

Introduction

Global Climate Models (GCMs) have evolved from the Atmospheric General Circulation Models (AGCMs) widely used for daily weather prediction. GCMs have been used for a range of applications, including investigating interactions between processes of the climate system, simulating evolution of the climate system, and providing projections of future climate states under scenarios that might alter the evolution of the climate system. The most widely recognized application is the projection of future climate states under various scenarios of increasing atmospheric carbon dioxide (CO₂).

At the core of a GCM is an AGCM that dynamically simulates the circulation of the atmosphere, including the many processes that regulate energy transport and exchange by and within the atmospheric flow. The basic atmospheric flow is represented by fundamental equations that link the mass distribution and the wind field. These equations are represented on a spherically spatial grid field that has many levels representing the depth of the atmosphere. The flow equations are modified by the representation of processes that occur on a scale *below* that of the grid—including such processes as turbulence, latent heat of condensation in cloud formation, and dynamic heating as solar and infrared radiation interact with atmospheric gases, aerosols, and clouds.

The oceans are at least as important as the atmosphere for the transport of energy. For that reason, the GCM also includes an Ocean General Circulation Model (OGCM) that simulates the circulation of the oceans. The OGCM is vital for climate simulations because the oceans represent a dynamic thermal reservoir that, through energy exchange with the atmosphere, dominates the evolution of the climate system. The specification of the processes that regulate heat, moisture, and momentum exchanges between the ocean and atmosphere is crucial to the integrity of a GCM.

Land surface, and how soil moisture and vegetation type regulate heat, moisture, and momentum with the atmosphere, plays a lesser but nevertheless important role in the simulation of climate. Soil moisture and vegetation respond to local precipitation and affect the exchange of heat, moisture, and momentum with the atmosphere over time. The soil moisture and vegetation (and their regulation of land-atmosphere exchange processes) respond to the climate on the shorter time-scale of weather systems but, due to the varying accumulation

of soil moisture, the influence of land surface on climate is on seasonal and interannual time-scales.

Surface ice sheets also have an important role in the evolution of the climate system. Their formation and expansion represent a lowering of the total energy of the climate system as a whole because latent heat is lost as water changes from the liquid to solid phase. Likewise, contraction of surface ice sheets represents an increase in the total energy of the climate system. The representation of heat, moisture, and momentum exchanges between ice surfaces and the atmosphere differs from that of land surfaces or ocean surfaces.

Dominating the climate system and its evolution are the radiation processes that regulate the input and output of energy. The shape of the rotating Earth, its distance from the Sun, and the characteristics of its orbit determine the nature of diurnal (daytime) and seasonal solar heating, including its maximum over the tropics. The shedding of energy by infrared radiation originates from the surface, from aerosols, from clouds, and from greenhouse gases of the atmosphere (CO₂, H₂O, O₃, etc.). The latitudinal spread of infrared loss radiation is less than for solar radiation and results in excess solar radiation being absorbed over the tropics but excess radiation shedding over higher latitudes.

A primary function of the climate system is to transport energy from the tropics to higher latitudes; globally, there is an equilibrium between solar radiation absorption and infrared radiation loss to space. Of course, with such a complex system there is rarely perfect balance. At times, especially during the cycle of seasons, Earth is accumulating radiation energy and warming, whereas at other times it is losing energy and cooling. But the rate of radiation loss varies with temperature and acts as a natural thermostat: when Earth warms, the infrared radiation loss to space increases such that it exceeds the solar input and warming ceases; when Earth cools, the infrared radiation loss to space decreases such that solar radiation exceeds the infrared radiation loss and cooling ceases.

The natural thermostat is more complex than this simple portrayal because different components of the climate system interact with limited bands of the infrared radiation spectrum. In particular, variation in surface characteristics, boundary layer aerosol characteristics, cloud height and distribution, and concentration of individual greenhouse gases can all affect the local infrared radiation loss to space across characteristic wavelengths with none affecting the full spectrum. Variations in each component, while acting

on a limited wavelength band, will affect the local magnitude of infrared radiation loss to space. Apart from water vapor concentration these variations are not necessarily temperature-dependent. Thus a change to the internal structure of the climate system for whatever reason will—all else being equal—lead to change in Earth's equilibrium temperature.

Within the AGCM there are many important processes that operate on scales below the resolution of the computational grid (sub-grid scale processes) and regulate local temperature, moisture, and momentum. Perhaps the most important of these is convection.

As described by Riehl and Malkus (1958), it is the “hot towers” of deep tropical convection that distribute the accumulating heat and latent energy of the tropical boundary layer through the troposphere. Correct specification of the mass flows within the cloud mass and its surroundings, including the updrafts and downdrafts, is essential for regulating the Hadley Cell circulation and the availability of tropical energy for transport to higher latitudes. Correct specification of the mass flows is also important if the local impact on temperature, water vapor, and momentum are to be quantified. Correctly specifying the mass flows remains a challenge to modelers.

In general, clouds and their interaction with the climate system are difficult to model. Clouds are an outcome of vertical motion and saturation, but the feedback to the circulation through radiation processes is sensitive. Although cloud fields tend to be regulated by the larger scale circulation, the processes leading to cloud formation and dissipation are operating on scales very much smaller than that of the computation grid, with individual clouds often occupying only a small part of a grid. Thus it is necessary for models to specify the climate interaction of a multitude of differing clouds across a grid space by a single process.

AGCMs are very complex and their output should be examined carefully and cautiously. In the physical sciences, mathematical models are often used to formalize a theory or hypothesis. For example, Newton's famous law of gravity formalized a statement of how objects fall or attract each other under ideal conditions (without wind or friction, for example). Note that in Newton's law “gravity” is undefined and remains undefined. Also, in this theory Newton was able to treat objects such as planets as point masses, a successful but auxiliary assumption. Textbook physics is largely made up of laws based on

such idealized situations (point masses, frictionless planes, ideal geometric bodies), and in approximations to ideal situations the models of physics work extremely well.

In the real world, however, inhomogeneity and complexity make the basic laws of physics less reliable. Whereas the breakage of simple rods under strain is easy to model and predict, earthquakes, which are also a breakage problem but occur in a complex setting of heterogeneous rock, are not predictable. Just because laws of physics are used does not mean a process is predictable; the climate prediction problem is not “just physics” as some scientists like to claim. It is also helpful to remember the laws of physics were developed by many rounds of experimentation, but it is not possible to conduct experiments at the scale of the whole Earth.

This means models themselves are being tested, in any study using them, to examine the behavior of a phenomenon. The definition of an atmospheric (climate) model is: a hypothesis [frequently in the form of mathematical statements] that describes the processes physically important to describe the workings of the atmosphere (climate and/or climatic change), that has physical consistency in the model formulation, and the agreement with the observations that serve to ‘test’ the hypothesis [i.e., the model]. The model is typically approximated for testing the hypothesis, but the model should conform to reality (AMS Glossary, 2000).

Once formulated, any atmospheric or climate model is simply a “box” that represents our best estimate of the workings of the atmosphere or climate. It is our best guess or approximation of the main processes of the system being represented and the mechanisms that link the processes. These models can be as complex or as simple as the model creators make them.

A model can be statistical or dynamic, and here we focus mainly on dynamic models, or what are called general circulation models. In a dynamic model, the system is represented in three dimensions, the characteristics of the system are specified at an initial time, and the system is allowed to evolve with time in accordance with the governing equations and boundary conditions that link essential processes.

An Atmosphere-Ocean General Circulation Model (AOGCM) is composed of seven basic mathematical equations with seven basic variables that describe the instantaneous state of the atmosphere over time. This represents a closed and solvable set of equations that can describe atmospheric motions and

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processes. The equations represent four basic physical principles; correct theories or models representing atmospheric motions will not violate these basic principles: (1) conservation of mass (dry mass and water mass), (2) conservation of energy, (3) conservation of momentum, and (4) elemental kinetic theory of gases. The equations are sequentially solved across the grid space for each time step such that the time directions of quantities at each grid point are affected by their neighbors according to the governing equations.

Physical processes for which there is no precise formulation, or where the formulation is on a scale below that able to be resolved in the model, are represented within these equations by *parameterizations*. Although generally based on observations and simple statistical relationships, the parameterizations often are no more than educated guesses. Representation of sub-grid scale processes is just one of the problems with models, but more computer programming resources are devoted to it than to the basic equations referred to above.

There are other problems with the models that manifest themselves as “computational error,” which with time will eventually cause the system evolution to depart from that of the prototype (e.g., Haltiner and Williams, 1980, Durran, 1999).

First, there simply are not enough data available to establish the initial conditions. For example, weather forecasts are made with data measured twice a day in the United States, but once a day in most other locations on the globe. Also, the highest density of weather information is garnered from stations over land, although data continue to be sparse over uninhabited regions. There are vast areas where the atmosphere is poorly represented or sampled by conventional land-based balloon soundings.

To some extent the data problem is overcome by the use of satellite information that has global coverage, albeit the satellite data differ somewhat from traditional thermometer-based observations. Atmospheric satellite sounding data differ from radiosonde data, and satellite-derived ocean skin temperature differs from ship and buoy observations of ocean surface temperature, to name just two. Differences between the satellite and traditional data need to be reconciled in the establishment of starting conditions and the evaluation of predictions.

Second, many atmospheric processes, such as thunderstorms, occur on space scales much smaller than a model’s resolution. Energy exchange processes occurring on scales below the resolution of the model

must therefore be approximated, or parameterized at the larger scale, and are therefore no longer mechanistic.

The inability to make the required observations with infinite precision means there is always some degree of measurement error or uncertainty associated with the initial conditions at the commencement of the forecast period. This uncertainty and its impact on the flow evolution can be measured by using differential equations and then making multiple runs of the model with slight variations in initial conditions. The error associated with the initial conditions amplifies into the flow structure and propagates through the system with time where it can render a model’s prediction unreliable in as short a time as four days (e.g., Lorenz, 1965).

This is not to imply that increased resolution in the models will fix this problem. In fact, there is some indication that further increasing the resolution will lead to diminishing improvements when examined against the cost, in computer time and budgets, of increasing the resolution.

Third, there is also some difficulty in representing the mathematical processes of the basic equations on the fixed grid space. The resolution of the model means the processes cannot be adequately specified and errors in representing the local gradients are amplified during the forecast period. Numerical finite difference methods are used generally to solve the GCM equations. For some operations there are several types of methods available (e.g., Wicker and Skamarock, 2002), making numerical modeling a matter of choosing the right tool for the job.

GCMs have the added complexity of coupling an ocean model, with its own difficulties of process specification, to an atmospheric model and regulating the energy exchange processes through the system by specified energy constraints. As more processes are introduced into the climate model—such as the energetics of the cryosphere, water storage in soils, and the changing of vegetation patterns—the model becomes considerably more complex and the potential for errors to be generated and to amplify in the output is increased.

All of these problems must be balanced against the amount of data a computer can process and how long it takes to produce a model simulation. Thus even this brief discussion and introduction of computer models demonstrates the skepticism through which the validity of model simulations should be evaluated. Unfortunately, there is little discussion by the IPCC about these problems inherent

to the models.

It also is critical to understand the difference between weather forecasting and the generation of climate projections or scenarios. Weather forecasting, in principle, is referred to as an initial value problem. Observational data are gathered, quality-controlled, and rendered to the grid space. This is no small problem because data are gathered from several sources, must be checked for consistency with other data, and then are rendered to the grid space in a manner consistent with our basic understanding and assumptions about atmospheric structure and behavior. The forecasts that evolve from these initial conditions are then constrained by the governing equations. To be useful, the evolution of the atmospheric flow must faithfully render the movement, development, and decay of the weather systems specified in the initial analysis. For weather forecasting models it is the structure and movement of the synoptic scale weather systems that is important. It is not as important to maintain global energy equilibrium over the relatively short prediction period of weather forecast.

How far out in time a useful forecast can be generated depends on the size and rotation rate of a planet, as well as the mixture of gases that make up the atmosphere. Using Earth's atmosphere and dimensions, it is widely accepted that a useful forecast can be made for no more than 10 to 15 days—referred to as the forecasting “wall.” Clearly, another strategy is needed in making both long-range weather and climate forecasts.

Climate modeling of the atmosphere also involves a boundary value problem. The climate system responds very quickly (relatively speaking) to changes in the pattern of radiation exchange to and from space and to changes in the pattern of heat and moisture exchange between the underlying surface and the atmosphere. Tectonic movements of the continents, on the other hand, are so slow that the land and ocean distribution is generally treated as a constant. But heat and moisture exchanges with the underlying surface vary significantly with ocean surface temperature distribution and vegetation states. Thus the concept of atmospheric climate can be thought of as a servant dependent on the underlying surface. To complicate matters, scientists are still not completely sure about how the exchange of heat and mass between the atmosphere and ocean (and land) take place.

The veracity of climate forecasts depends not only on the ability of the general circulation equations

to reproduce the flow structures but also on the specification of the many sub-grid scale processes that regulate energy, moisture, and momentum exchanges at these scales. Errors in any of these specifications will bias local energy accumulations and become evident as a false trend in the evolution of local climate indices. Many of the sub-grid scale exchanges are functions of local temperature or temperature gradient; locally developing biases will propagate spatially with time.

Thus the main distinction between weather forecast models and climate models is that, in the former, the objective is to specify the individual weather systems and reproduce their travel and decay, together with the development of new systems, over time. For climate models the interest is not in individual weather systems that cannot be replicated beyond about two weeks, but in the subtle changes in energy reservoirs over time, especially warming land surfaces, the ocean surface mixed layer, and cryosphere extent. This difference in objective is very large in principle.

There are two distinct types of climate models. Diagnostic, or equilibrium climate models (ECMs) represent steady-state or unchanging processes with time. The ECM is most commonly solved for climatic means and variations and can employ statistical or dynamical methods, or some combination of these, to generate a future climate.

In the second type of climate model, the Prognostic, changes in variables with time are crucial. The time variation for a given variable is the desired output (i.e., a time series). Thus climatic means and variances are changing and can be calculated and compared over limited time intervals.

Both types of models are employed in the study of climate. Generally, the diagnostic model is simpler and produces numerical output faster. Prognostic models are more complex. Either modeling technique can be utilized to create future climate projections or scenarios.

One way of making a climate model projection is to start with today's conditions in a weather forecast model retooled for climate simulation. Researchers “add” carbon dioxide to replicate the rise in greenhouse gases and then run the model to see what output it produces. This approach would seem to be ideal, except there are several atmosphere-ocean interaction processes acting on multiyear to multidecadal time scales that models have not yet mastered. Examples of these phenomena are the El Niño–Southern Oscillation (ENSO, or El Niño and La

Niña), the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO), and, on longer time scales, the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). The physical workings of these processes are not yet well understood, thus it is not surprising there is difficulty in modeling them. The effect of these cycles on regional and even global climate is not trivial, and failure to understand a phenomenon does not excuse leaving it out of a model, which is often done. Omitting such phenomena subjects the models to additional errors and failure.

In evaluating model reliability, the standard assumption has been to compare model output with observations over a given period of Earth's past climate, e.g. since 1850. Doing so, however, requires subjective adjustments to the model; for example, in order to replicate estimated changing solar intensity and atmospheric aerosol loading. These adjustments create additional sources of uncertainty, as limited data exist in the past and knowledge about internal variability and the role of multidecadal-to-century-scale climate cycles is also restricted.

Perhaps it is in light of such limitations that in Chapter 9 of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) (e.g., IPCC, 2013-I) it is conceded that "climate models provide realistic simulations of the large-scale features in the climate system and reproduce observed historical change with only some fidelity. The climate sensitivity of current models has not changed dramatically from that of models assessed in the AR4, in spite of many improvements to the models' representation of physical processes."

Another strategy in creating model projections is to first allow the climate model to equilibrate; i.e., to find a steady climate state under control conditions and then again under conditions that may exist in the future (e.g., double the CO₂ concentration). Then, one can analyze the differences in equilibrium climates in order to project how the climate of this future time will look. It should be kept in mind that a steady-state climate may not exist in nature.

What about projections that show global temperature may rise by as much as 1° C to 6° C by 2100 (e.g., IPCC, 2007-I)? Such projections are based on a strategy in which a model is run many, many times from a particular set of initial conditions followed by slightly altered initial conditions. This is called a model ensemble. Generally, due to many of the problems discussed here and to the nature of the basic equations used in the model, the large range in

global temperature projections is a natural result of the ensemble technique. The more times a model is run and the longer the time period of evolution used, the greater the spread in the range of the predicted variable, such as global temperature. This is referred to as sensitivity to initial conditions (SDIC). Such behavior is inherent in any system that displays chaotic characteristics, as does Earth's climate system. Chaos theory is another name for the study of such nonlinear dynamics, which are represented in the raw forms of the basic equations.

The IPCC places great confidence in the ability of GCMs to simulate future climate and attribute observed climate change to anthropogenic emissions of greenhouse gases. It says "climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate ... and past climate changes. ... There is considerable confidence that Atmosphere-Ocean General Circulation Models (AOGCMs) provide credible quantitative estimates of future climate change, particularly at continental and larger scales" (IPCC, 2007-I, p. 591).

The IPCC's confidence in the models, however, is likely considerably overstated. The magnitude of the range of projected temperature responses to a doubling of atmospheric CO₂ itself suggests there are large errors and limitations in the models that must be overcome. To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes described above but also the chemical and biological processes that influence climate over long time periods. In addition, current computational errors resulting from finite grid resolution must be overcome so as not to introduce growing biases. And as a final step, model output must be compared with and evaluated against real-world observations.

The remainder of this chapter delves further into the complexities and problems inherent to computer modeling of the climate system. Other chapters in this volume serve to evaluate the model projections using real-world data observations.

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1.1 Model Simulation and Forecasting

1.1.1 Methods and Principles

J. Scott Armstrong, a professor at The Wharton School of the University of Pennsylvania and a leading figure in forecasting, has pointed out that forecasting is a scientific discipline built on more than 70 years of empirical research, with its own institute (International Institute of Forecasters, founded in 1981), peer-reviewed journals (*International Journal of Forecasting* and *Journal of Forecasting*), and annual International Symposium on Forecasting. The research on forecasting has been summarized as scientific principles, currently numbering 140, that must be observed in order to make valid and useful forecasts (*Principles of Forecasting: A Handbook for Researchers and Practitioners*, edited by J. Scott Armstrong, Kluwer Academic Publishers, 2001).

When physicists, biologists, and other scientists who are unaware of the rules of forecasting attempt to make climate predictions, their forecasts are at risk of being no more reliable than those made by non-experts, even when they are communicated through complex computer models (Green and Armstrong, 2007). In other words, when faced with forecasts by scientists, even large numbers of very distinguished scientists, one cannot assume the forecasts are scientific. Green and Armstrong cite research by Philip E. Tetlock (2005), a psychologist and now

professor at the University of Pennsylvania, who “recruited 288 people whose professions included ‘commenting or offering advice on political and economic trends.’ He asked them to forecast the probability that various situations would or would not occur, picking areas (geographic and substantive) within and outside their areas of expertise. By 2003, he had accumulated more than 82,000 forecasts. The experts barely, if at all, outperformed non-experts, and neither group did well against simple rules” (Green and Armstrong, 2007). The failure of expert opinion to provide reliable forecasts has been confirmed in scores of empirical studies (Armstrong, 2006; Craig *et al.*, 2002; Cerf and Navasky, 1998; Ascher, 1978) and illustrated in historical examples of wrong forecasts made by leading experts, including such luminaries as Ernest Rutherford and Albert Einstein (Cerf and Navasky, 1998).

In 2007, Armstrong and Kesten C. Green of the Ehrenberg-Bass Institute at the University of South Australia conducted a “forecasting audit” of the IPCC *Fourth Assessment Report* (Green and Armstrong, 2007). The authors’ search of the contribution of Working Group I to the IPCC “found no references ... to the primary sources of information on forecasting methods” and “the forecasting procedures that were described [in sufficient detail to be evaluated] violated 72 principles. Many of the violations were, by themselves, critical.”

Green and Armstrong found the IPCC violated “Principle 1.3 Make sure forecasts are independent of politics.” The two authors write, “this principle refers to keeping the forecasting process separate from the planning process. The term ‘politics’ is used in the broad sense of the exercise of power.” Citing David Henderson (2007), a former head of economics and statistics at the Organization for Economic Cooperation and Development (OECD), Green and Armstrong state, “the IPCC process is directed by non-scientists who have policy objectives and who believe that anthropogenic global warming is real and dangerous.” They thus conclude:

The forecasts in the Report were not the outcome of scientific procedures. In effect, they were the opinions of scientists transformed by mathematics and obscured by complex writing. Research on forecasting has shown that experts’ predictions are not useful in situations involving uncertainty and complexity. We have been unable to identify any scientific forecasts of global warming. Claims that the Earth will get warmer have no more credence than saying that it will get colder.

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Scientists working in fields characterized by complexity and uncertainty are apt to confuse the output of models—which are nothing more than a statement of how the modeler believes a part of the world works—with real-world trends and forecasts (Bryson, 1993). Computer climate modelers frequently fall into this trap and have been severely criticized for failing to notice their models fail to replicate real-world phenomena by many scientists, including Balling (2005), Christy (2005), Essex and McKittrick (2007), Frauenfeld (2005), Michaels (2000, 2005, 2009), Pilkey and Pilkey-Jarvis (2007), Posmentier and Soon (2005), and Spencer (2008).

Canadian science writer Lawrence Solomon (2008) asked many of the world's leading scientists active in fields relevant to climate change for their views on the reliability of computer models used by the IPCC to detect and forecast global warming. Their answers showed a high level of skepticism:

- Prof. Freeman Dyson, professor of physics at the Institute for Advanced Study at Princeton University and one of the world's most eminent physicists, said the models used to justify global warming alarmism are “full of fudge factors” and “do not begin to describe the real world.”
- Dr. Zbigniew Jaworowski, chairman of the Scientific Council of the Central Laboratory for Radiological Protection in Warsaw and former chair of the United Nations Scientific Committee on the Effects of Atomic Radiation, a world-renowned expert on the use of ancient ice cores for climate research, said the U.N. “based its global-warming hypothesis on arbitrary assumptions and these assumptions, it is now clear, are false.”
- Dr. Richard Lindzen, professor of meteorology at the Massachusetts Institute of Technology and member of the National Research Council Board on Atmospheric Sciences and Climate, said the IPCC is “trumpeting catastrophes that couldn't happen even if the models were right.”
- Prof. Hendrik Tennekes, director of research at the Royal Netherlands Meteorological Institute, said “there exists no sound theoretical framework for climate predictability studies” used for global warming forecasts.
- Dr. Richard Tol, principal researcher at the Institute for Environmental Studies at Vrije

Universiteit and adjunct professor at the Center for Integrated Study of the Human Dimensions of Global Change at Carnegie Mellon University, said the IPCC's *Fourth Assessment Report* is “preposterous ... alarmist and incompetent.”

- Dr. Antonino Zichichi, emeritus professor of physics at the University of Bologna, former president of the European Physical Society, and one of the world's foremost physicists, said global warming models are “incoherent and invalid.”

Dyson has written elsewhere, “I have studied the climate models and I know what they can do. The models solve the equations of fluid dynamics, and they do a very good job of describing the fluid motions of the atmosphere and the oceans. They do a very poor job of describing the clouds, the dust, the chemistry, and the biology of fields and farms and forests. They do not begin to describe the real world that we live in” (Dyson, 2007).

Many of the scientists cited above observe computer models can be “tweaked” to reconstruct climate histories after the fact. But this provides no assurance that the new model will do a better job of forecasting future climates, and it points to how unreliable the models are. Individual climate models often have widely differing assumptions about basic climate mechanisms but are then “tweaked” to produce similar forecasts. This is nothing like how real scientific forecasting is done.

Kevin Trenberth, a lead author along with Philip D. Jones of Chapter 3 of the Working Group I contribution to the IPCC's *Fourth Assessment Report*, replied to some of these scathing criticisms on the blog of the science journal *Nature*. He argued “the IPCC does not make forecasts” but “instead proffers ‘what if’ projections of future climate that correspond to certain emissions scenarios” and then hopes these “projections” will “guide policy and decision makers” (Trenberth, 2007). He says “there are no such predictions [in the IPCC reports] although the projections given by the Intergovernmental Panel on Climate Change (IPCC) are often treated as such. The distinction is important.”

This defense is hardly satisfactory. As Green and Armstrong (2007) point out, “the word ‘forecast’ and its derivatives occurred 37 times, and ‘predict’ and its derivatives occurred 90 times in the body of Chapter 8 of the Working Group I report, and a survey of climate scientists conducted by those same authors found “most of our respondents (29 of whom were

IPCC authors or reviewers) nominated the IPCC report as the most credible source of forecasts (not ‘scenarios’ or ‘projections’) of global average temperature.” Green and Armstrong conclude, “the IPCC does provide forecasts.”

Green and Armstrong subsequently collaborated with Willie Soon in conducting validation tests of the IPCC forecasts of global warming (Green, Armstrong, and Soon 2009). To do so, they tested whether the warming-trend forecasts used by the IPCC are more accurate than the standard benchmark forecast that there will be no change. They tested the IPCC’s “business as usual” 0.03°C p.a. forecast and the no-change forecast from one to 100 years ahead on a rolling basis over the period of exponentially increasing human CO₂ emissions from 1851 to 1975. The procedure generated 7,550 forecasts from each of the forecasting procedures.

The Green, Armstrong, and Soon validation test was a weak one, in that the IPCC forecasts were tested against historical data (HadCRUt3) the IPCC modelers knew exhibited a warming trend. Green, Armstrong, and Soon therefore were surprised to find the errors from the IPCC warming trend forecasts were nearly eight times greater than the errors from the no-change forecasts. For the longer 91 to 100 years-ahead forecast horizons, the IPCC errors were nearly 13 times greater for the 305 forecasts. The no-change forecasts were so accurate in the validation test that the authors forecast annual global mean temperatures will be within 0.5°C of the 1988 figure for the next 100 years. For public policy and business planning purposes, it is hard to see that any economic benefit could be obtained from forecasts that were less accurate than forecasts from the no-change model. The implication of the Green, Armstrong, and Soon forecasts is that the best policy is to do nothing about global warming. Their findings did not, however, stop the claims that “we are at a turning point” and “it is different this time.”

If public policy to address global warming is to be made rationally, it must be based on scientific forecasts of (1) substantial global warming, the effects of which are (2) on balance seriously harmful, and for which (3) cost-effective policies can be implemented. Armstrong, Green, and Soon (2011) refer to these logical requirements of policymaking as “the 3-legged stool” of global warming policy. A failure of any leg would invalidate policies. To date, there are no evidence-based forecasts to support any of the legs.

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1.1.2 Computational Issues

To commemorate the publication of the 100th volume of the journal *Climatic Change*, Norman Rosenberg (Rosenberg, 2010) was asked to contribute an overview paper on progress that had occurred since the journal's inception in the interrelated areas of climate change, agriculture, and water resources. Rosenberg accepted and at the age of 80 conducted his review quite admirably.

He began by noting the “overarching concern” of the volumes he edited was “to gain understanding of how climatic change affects agricultural production, unmanaged ecosystems and water resources; how

farmers, foresters and water managers can strengthen these sectors against the negative impacts of climatic change and capitalize on positive impacts if any; how they can adapt to impacts that cannot be so modified or ameliorated and how they can contribute directly or indirectly to mitigation of anthropogenic climatic change—as, for example, through soil carbon sequestration and the production of biomass to substitute in part for the fossil fuels that are adding CO₂ to the atmosphere.”

Rosenberg writes in his closing paragraph, “it seems difficult to say with assurance that the ‘state-of-the-art’ in projecting climatic change impacts on agriculture and water resources and unmanaged ecosystems is, today, that much better than it was 30 years ago,” noting “the uncertainty and lack of agreement in GCMs is still too great.” He reported, “much can and has been learned about possible outcomes,” but “for actual planning and policy purposes we are still unable to assure those who need to know that we can forecast where, when and how much agriculture (as well as unmanaged ecosystems and water resources) will be affected by climatic change.”

A similarly pessimistic commentary on the state of climate modeling appeared in 2010 in *Nature Reports Climate Change*. Kevin Trenberth, head of the Climate Analysis Section of the National Center for Atmospheric Research in Boulder, Colorado (USA), writes that one of the major objectives of upcoming climate modeling efforts will be to develop “new and better representations of important climate processes and their feedbacks.” The new work, Trenberth wrote, should increase “our understanding of factors we previously did not account for ... or even recognize.”

In expressing these sentiments, Rosenberg and Trenberth gave voice to the concerns of many scientists who are skeptical of the reliability of GCMs. Such concerns should not be misinterpreted as “denial.” Trenberth, at least, would deny being a “skeptic” of the theory of anthropogenic global warming. It is, rather, the humility of true scientists who—attempting to comprehend the complexity of the world of nature and its innermost workings—are well aware of their own limitations and those of all seekers of scientific truths. Although much has been learned, as Rosenberg and Trenberth outline in their respective essays, what is known pales in comparison to what is required “for actual planning and policy purposes,” as Rosenberg describes it, or “certainty” as Trenberth puts it.

In contrast, consider a paper that fails to recognize any such problems. Published in the *Proceedings of the National Academy of Sciences of the United States of America* and written by Susan Solomon (a co-chair of the IPCC's 2007 Working Group 1 report for AR4) and three coauthors, it claims to show "climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop" (Solomon *et al.*, 2009). In the virtual world of computer-run climate models, that may be the case, but that may not be true of the real world. Consider, for example, that the discernible climate signal from a major volcanic eruption is lost after only a few years.

In their paper, Solomon *et al.* set forth three criteria they say should be met by the modeled climatic parameters they studied: "(i) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (ii) the phenomenon[a] [are] based upon physical principles thought to be well understood, and (iii) projections are available and are broadly robust across models."

Real-world data provide little or no support for the first criterion (as discussed in other chapters of this volume). The global warming of the past few decades was part of a much longer warming trend that began in many places throughout the world a little more than three centuries ago (about 1680) with the dramatic "beginning of the end" of the Little Ice Age (LIA, see Figure 1.1.1), well before there was any significant increase in the air's CO₂ content. This observation suggests a continuation of whatever phenomenon—or combination of phenomena—may have caused the greater initial warming may have caused the lesser final warming, the total effect of which has been to transport Earth from the chilly depths of the Little Ice Age into the relative balminess of the Current Warm Period.

Climate history is discussed in greater detail in Chapter 4, but it is useful to note here that Earth's current temperature is no higher now (and may be slightly less) than it was during the peak warmth of the Medieval Warm Period (MWP), when there was more than 100 ppm less CO₂ in the atmosphere there is today. Consequently, since the great MWP-to-LIA cooling phase occurred without any significant change in the atmosphere's CO₂ concentration, the opposite could occur just as easily. The planet could warm, and by an equal amount, just as it actually did over the past three centuries without any help from an increase in the atmosphere's CO₂ content.

Regarding the second criterion of Solomon *et al.*,

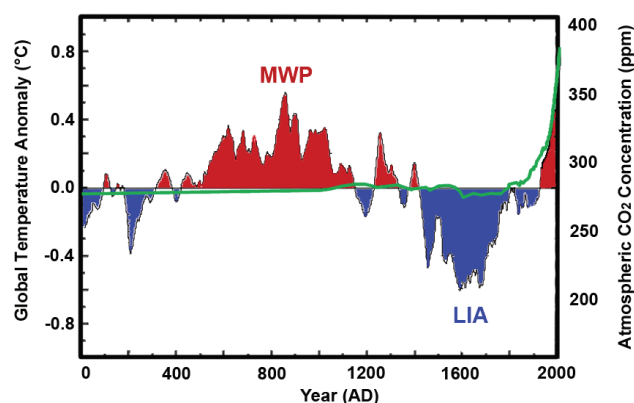


Figure 1.1.1. The mean relative temperature history of the Earth (blue, cool; red, warm) over the past two millennia highlighting the Medieval Warm Period (MWP) and Little Ice Age (LIA), together with a concomitant history of the atmosphere's CO₂ concentration (green). Adapted from Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* 19: 93–100.

studies reported in this volume (see Chapter 2) also show there are non-modeled chemical and biological processes that may be equally as important as the changes in radiation fluxes associated with carbon dioxide employed in the models. The chemical and biological processes are simply not as "well understood" as Solomon *et al.* claim. A highly selective reading of the literature is required to miss the repeated admissions by leading researchers of the uncertainty and outright ignorance of underlying processes that undermine the reliability of GCMs.

Regarding the third criterion of Solomon *et al.*, many computer model projections are "available and are broadly robust across models." To say such models are "robust" implies they are producing stable climate simulations that are similar to observations. But these models often diverge so greatly in their assumptions and in their specific spatial and temporal projections that they cannot be said to validate each other. Additionally, there is no scientific basis for the often-made claim that an average from such discordant projections can be meaningful. Furthermore, many studies have identified real-world data that contradict what the models say should be occurring.

A good example of an admission of the wide range of uncertainty that undermines GCMs appears in Woollings (2010): "the spread between the projections of different models is particularly large

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over Europe, leading to a low signal-to-noise ratio. This is the first of two general reasons why European climate change must be considered especially uncertain. The other is the long list of physical processes which are very important for defining European climate in particular, but which are represented poorly in most, if not all, current climate models.”

Woollings cited several examples of key atmospheric processes affecting the climate of Europe that models currently do not simulate well, noting (1) the location of the jet stream over northern Europe in most models diverges from reality, (2) zonal flow is biased too far south in most models, (3) the models can’t simulate or explain the North Atlantic Oscillation with sufficient magnitude to match historical data, and (4) heat waves and droughts, such as the summer 2010 Moscow heat wave and fires, are caused by blocking, a process the models are currently unable to simulate reliably even in weather forecast models (e.g., Matsueda, 2011), let alone climate models.

In addition, for several key processes the models produce widely varying predictions. The atmospheric circulation response to warming in climate models, for example, is highly variable, as is the change in storm intensity, the projected change in the jet stream, and changes in temperature. It is particularly noteworthy that Europe is predicted to warm less than most Northern Hemisphere sites due to the slowing of the Gulf Stream providing reduced northward heat transport, a factor Woollings noted the models do not simulate well.

It is thus easy to recognize that current climate models are unable to achieve the degree of accuracy necessary in the details of atmospheric circulation that are critical to replicating current weather events, such as droughts, heat waves, and major storms that contribute to the characteristic climate in Europe. Any assertion that frequency or intensity of these events can be forecast 100 years in the future under a changed climate is simply false, and claims about negative impacts of climate change in Europe are based upon no specific modeling skill.

Another problem with climate models is climate drift. Sen Gupta *et al.* (2012) write, “even in the absence of external forcing, climate models often exhibit long-term trends that cannot be attributed to natural variability,” and they state “this so-called climate drift arises for various reasons,” such as “deficiencies in either the model representation of the real world or the procedure used to initialize the

model.” They note, however, that “significant efforts by the climate modeling community have gone into reducing climate drift.” Nevertheless, they write, “climate drift still persists.”

Sen Gupta *et al.* “quantify the size of drift relative to twentieth-century trends in climate models taking part in the Coupled Model Intercomparison Project phase 3 (CMIP3),” which they say “was used to inform the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).”

According to the seven Australian scientists, their analysis determined that below 1-2 km in the deep ocean, or for depth-integrated properties, drift generally dominates over any forced trend. They report drift in sea level can be large enough to *reverse the sign* of the forced change, “both regionally and in some models for the global average.” In addition, because surface drift is spatially heterogeneous, they say “the regional importance of drift for individual models can be much larger than the global figures suggest.” As an example, they note “a typical error in calculating a regional forced sea surface temperature trend in the Bjerknes Center for Climate Research Bergen Climate Model, version 2.0 (BCM2.0), CSIRO Mk3.0, and GISS-EH models without accounting for drift would be 30% to 40%.” Because this is an average value, still-larger errors would be expected at some locations.

While providing some suggestions for addressing climate modeling drift problems, Sen Gupta *et al.* write, “in the absence of a clear direction forward to alleviate climate drift in the near term, it seems important to keep open the question of flux adjustment within climate models that suffer from considerable drift.” They indicate “flux adjustments are nonphysical and therefore inherently undesirable” and “may also fundamentally alter the evolution of a transient climate response,” citing the work of Neelin and Dijkstra (1995) and Tziperman (2000).

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1.1.3 Dealing with Chaos

1.1.3.1 Chaotic Systems

The ability of atmosphere-ocean GCMs to predict the climatic effects of human alterations of greenhouse gases and other factors cannot be tested directly with respect to a point in time a hundred years in the future. However, it is still possible to determine whether those models can in principle make such predictions with a reasonable degree of accuracy.

One way to evaluate this ability is to consider the effects of errors in system initial values. If a system is well-behaved, small initial errors will lead to small future errors or even damped responses. In a chaotic system, on the other hand, small initial errors will cause trajectories to diverge over time; for such a system (or model), true predictability is low to nonexistent. This does not mean realistic behavior in the statistical sense cannot be simulated, only that detailed predictability (will it rain 60 days from now, or how much will it rain this year) is impossible.

1.1.3.2 Sensitivity Dependence

One of the characteristics of chaotic systems, such as the fluid we call our atmosphere, is *sensitive dependence on the initial conditions* (SDIC). SDIC

means one can take an initial state for our atmosphere, including all the temperature, pressure, and other measurements, and put them into a computer model and generate, for example, a 48-hour weather forecast. If we use an identical model but adjust these initial measurements by small amounts representing error, it is possible to generate a 48-hour forecast much different from the first one.

In weather forecasting, for example, some 15 to 20 model runs are strategically generated in order to examine how much “spread” there is between the multiple runs. If the forecasts show little spread, a weather forecaster can be more confident in the model projections; if there is a great deal of spread, the forecaster must rely on other tools to develop a forecast.

In a study addressing initial value errors, Collins (2002) used the HadCM3 model, the output of which at a given date was used as the initial condition for multiple runs in which slight perturbations of the initial data were used to assess the effect of a lack of perfect starting information, as can often occur in the real world. The results of the various experimental runs were then compared to those of the initial control run, assuming the degree of correlation of the results of each perturbed run with those of the initial run is a measure of predictability.

Collins found “annual mean global temperatures are potentially predictable one year in advance” and “longer time averages are also marginally predictable five to ten years in advance.” In the case of ocean basin sea surface temperatures, coarse-scale predictability ranges from one year to several years were found. But for land surface air temperature and precipitation, and for the highly populated northern land regions, Collin concludes, “there is very little sign of any average potential predictability beyond seasonal lead times.”

King *et al.* (2010) used an atmospheric GCM to gauge the ability of models to reproduce observed climate trends from the 1960s to the 1990s using model ensembles. They also attempted to quantify the influence of driving factors both internal and external such as sea ice, stratospheric ozone, greenhouse gases, and internal atmospheric variability. Their research was performed using a 100-member ensemble with climatological sea surface temperatures (SSTs) over the globe from 1870 to 2002. Three tests with ten members each were conducted, prescribing SSTs for tropical oceans, for the Indian and Pacific Ocean, and for the tropical Pacific, respectively.

The authors found only when the tropical SSTs were specified were the trends reproduced with a high degree of correlation (correlation = 0.80). The amplitude of these was only about 25 percent that of the observed amplitudes for the ensemble mean. Individual ensemble members were at a maximum of 50 percent of the observed trends. The authors acknowledge “the underestimate of the trend amplitude is a common difficulty even for state-of-the-art AGCMs, as well as coupled models with external forcings.” The authors also found Arctic sea ice, CO₂ changes, and stratospheric dynamics and chemistry also contributed to these trends separately and were each major contributors to the decadal variations and trends. None of these forcings separately or together was able to fully represent the observed trends during the 1958–1996 period. None of the ensemble members could reproduce the amplitude of the trends reliably. As stated by the authors, something was missing: “another major player in decadal climate variability is the ocean circulation, which is not accounted for at all by the study here.”

A frequent criticism of GCMs is their inability to effectively render past climate. The models used by organizations such as the Intergovernmental Panel on Climate Change are similar to those used in the King *et al.* study above. In King *et al.*’s paper the model performed at its best only when tropical SSTs were included. The authors also cite the need to include ocean dynamics. But even the use of ensemble techniques allowed for only limited success by the models. Clearly, caution should be taken in interpreting future climate scenarios.

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1.1.4 Carbon Dioxide Forcing

The interaction between atmospheric carbon dioxide and Earth’s radiation field is at the heart of the anthropogenic climate change debate. In particular, the effect of including in GCMs increasing concentrations of carbon dioxide has been to project

global temperature increases that have given rise to additional climate-related concerns about potentially devastating impacts on the biosphere. The alleged possibility of ecosystem extinctions is one example of such concerns that underlie calls to halt carbon dioxide emissions.

There is a long history of scientific debate linking carbon dioxide, through its interaction with Earth’s radiation field, to global climate and its variability. The French mathematician Joseph Fourier (1824, 1827) noted Earth should be colder than it is, given its place in the solar system and the strength of solar radiation it absorbs. Fourier’s explanation of the apparently abnormal warmth was linked to the insulating properties of Earth’s atmosphere. Earth’s greenhouse effect was claimed to be an outcome of absorption of radiation emitted from Earth’s surface by gases in the atmosphere, which warmed the lower atmosphere and reduced infrared radiation emissions to space.

Credence was given to Fourier’s hypothesis via a series of measurements carried out by the English physicist John Tyndall beginning in the late 1850s. Tyndall passed infrared (IR) radiation through different atmospheric gases and measured the absorption. He demonstrated water vapor is a strong absorber of infrared radiation, as is carbon dioxide and some other minor atmospheric constituents.

The Swedish chemist Svante Arrhenius (1896) hypothesized that the shifts of Earth’s temperature from glacial to interglacial conditions might be explained by fluctuating changes in the atmospheric concentration of carbon dioxide. In simple terms, when carbon dioxide concentrations are low, there is less absorption of infrared radiation in the atmosphere and temperatures drop. But when concentrations are high, the hypothesis suggests an increased radiative absorption of CO₂ that keeps Earth’s temperature warmer. The reason given for the hypothesized fluctuating change in carbon dioxide concentration was varying volcanic activity: When volcanic activity was low, less carbon dioxide was being emitted to the atmosphere than photosynthesis was removing, and atmospheric CO₂ concentration fell; when activity was high, the atmospheric concentration increased.

Arrhenius’ hypothesis linking glacial conditions to low carbon dioxide concentrations fell from favour, not because of the links to the greenhouse theory but because it became apparent that recurring glacial events were regular and not explained by volcanic activity. Nevertheless, through the twentieth century the notion that increasing carbon dioxide concen-

tration in the atmosphere would increase global temperature remained an active hypothesis. Systematic measurements of atmospheric carbon dioxide commenced at Mauna Loa Observatory, Hawaii, during the 1957–58 International Geophysical Year. Measurements at other sites have followed to give a global network of CO₂ monitoring and confirm a steadily increasing concentration of atmospheric CO₂. The increase has been attributed to human activity, especially the burning of fossil fuels.

The development of the first GCMs provided an opportunity to test the sensitivity of the climate system to a CO₂ forcing. The first GCMs were rather simple in construction, with the oceans represented as a shallow swamp (Manabe *et al.*, 1965; 1970). Nevertheless, in steady-state the models were able to represent the main features of Earth's climate, including the zonal gradients of temperature and pressure and the main wind systems. Manabe *et al.* (1979) used a similar model to examine the effects of additional carbon dioxide. The GCM was run under conditions of 300 ppm carbon dioxide (1 X CO₂) and 1,200 ppm carbon dioxide (4 X CO₂) and each came to steady-state after about 12 years; the difference in global average surface air temperature between the two concentrations was 4.1°C.

In a general review of carbon dioxide and climate, Manabe (1983) outlined the principles of a simple radiation-convection model that potentially yielded an indicative estimate of the sensitivity of surface temperature to carbon dioxide forcing. First, it was noted earlier surface energy budget models underestimated the sensitivity because of unrealistically large heat and moisture exchanges with the boundary layer, a consequence of the assumption of constant temperature and specific humidity for that layer. An alternative approach was to drive the model by changing the radiative divergence of the atmospheric layers as carbon dioxide concentration increased; net atmospheric radiation loss was offset by vertical convective mixing of heat and moisture from the surface, the surface was assumed to have no heat capacity, and by convective adjustment the tropospheric temperature lapse rate was constrained to no more than the saturated adiabatic lapse rate of 6.5°C/km. Such models consistently returned a surface temperature rise of between 1.5°C and 2.3°C for a doubling of the atmosphere's carbon dioxide concentration.

The Manabe review also outlined contemporary results from GCM forced by doubling of carbon dioxide concentration to a new steady-state. Such

models show consistent responses, including: (1) stronger warming over polar regions due to positive feedback as snow and sea ice melt to change surface albedo, (2) amplification of tropical upper tropospheric warming due to the regulation of temperature by convective mixing, and (3) a temperature increase in the Northern Hemisphere greater than that of the Southern Hemisphere. Results from different models, each constructed on similar principles, demonstrated a broader spread in the estimates of climate sensitivity, from 2°C to 3.9°C for a doubling of carbon dioxide concentration.

One characteristic of these early models was the limited impact of the absence of ocean circulation. It was only over the North Atlantic region that temperatures had a cold bias from the lack of ocean heat transport.

On the basis of such computer model findings, an October 1985 U.N.-cosponsored conference in Villach, Austria (Bolin *et al.*, 1985) issued a statement asserting “many important economic and social decisions are being made today on long-term projects ... all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century.” The statement specifically claimed a doubling of carbon dioxide concentration would lead to a global temperature rise between 1.5°C and 4.5°C. It also asserted the global temperature rise of between 0.3°C and 0.7°C during the twentieth century was consistent with the carbon dioxide increase, implying a cause-and-effect relationship, with CO₂ as the cause.

GCMs have evolved since those early days. Increased computing power has enabled higher spatial resolution both horizontally and vertically. The models also better represent physical processes, couple dynamic ocean and atmospheric circulations, and include a range of bio-geo-chemical processes. Nevertheless, there remain fundamental problems with their representation and treatment of rising carbon dioxide and its potential impact on climate.

Early indicative measures of climate sensitivity were obtained via relatively simple models constrained by three essential assumptions: (1) there is an equilibrium balance between the solar radiation absorbed by the system and the infrared radiation emitted to space, (2) the net radiation loss from the atmosphere (solar and infrared) is offset by heat and latent energy exchange from the surface, and (3) the

net radiation excess at the surface (solar and infrared) is offset by the surface-atmosphere heat and latent energy exchange plus heat that goes into surface reservoirs (latent heat melting ice, warming of the land surface, and warming of the ocean).

The concern over climate forcing by increasing the carbon dioxide content of the atmosphere arises because changes in the absorption and emission of infrared radiation by CO₂ in the active wavebands (in the range 12-18μm) vary the intensity of infrared radiation propagating both upwards and downwards throughout the atmosphere, and hence the net radiation transfer from the surface to space. By increasing the concentration of carbon dioxide, the emission to space in the active wavebands emanates from higher in the atmosphere where temperatures are colder. As a consequence, the emission of radiation to space is reduced across the carbon dioxide wavebands. To maintain balance in the overall infrared emission of energy to space it is therefore presumed that global temperatures would rise and increase the emission intensity across non-carbon dioxide wavebands.

As carbon dioxide concentrations increase so too does the intensity of back radiation at the surface across the active wavebands of CO₂, and because this radiation emanates from a lower and warmer layer of the atmosphere, the magnitude of the back radiation increases. Consequently, the net infrared radiation emanating from the surface is reduced, causing a rise in temperature that generates increased heat exchange and evaporation. This surface warming also contributes to an increase in convective instability.

In addition to the reduction in infrared radiation to space and the reduction in net infrared radiation loss from the surface, there is also a reduction in radiation flux divergence (cooling) over the atmosphere, because the former is greater than the latter. The reduction in radiative cooling is effectively a reduction in the rate of generation of convective instability necessary for distribution of heat and latent energy from the surface and through the atmosphere. This is an additional, albeit indirect, factor leading to surface warming, which convectively influences tropospheric temperature.

By convention, the sensitivity of surface temperature to carbon dioxide forcing is expressed as the relationship between the reduction in infrared radiation to space and the increase in surface temperature. However, as described above, the reduction in infrared radiation is confined to the carbon dioxide wavebands. As Earth's climate

responds to increasing carbon dioxide, there is no reduction in emission to space, only a shift in the distribution of energy across the infrared spectrum. The shift can be achieved by a general warming (as described in the sensitivity relationship) or by a change in circulation. An enhancement of convective overturning will both expand the area occupied by subtropical subsidence and increase the poleward transport of heat. Enhanced subsidence will dry those regions of the atmosphere, allowing emission to space across the water vapor bands to emanate from a lower and warmer region of the troposphere. Increased poleward transport of heat will warm the middle and high latitude troposphere. Both effects can increase the infrared radiation to space, but neither necessarily leads to warming of the surface.

Held and Soden (2006) analyzed the set of GCMs used for the IPCC's *Fourth Assessment Report* (Solomon *et al.* 2007) and concluded there was a reduction in overturning as the model Earth warmed with increasing atmospheric carbon dioxide. Their analysis suggests the reason for the reduction in convective overturning was due to the differing rates of increase in atmospheric water vapor increase and surface evaporation as temperature increased. In the models the atmospheric water vapor mass increased according to the Clausius Clapeyron relationship of about 7 percent per degree C (%/C), whereas the surface evaporation increased at only about 2%/C. As atmospheric water vapor increased, the convective clouds processed the water vapor mass flow more efficiently than the rate at which water vapor was being delivered to the boundary layer by surface evaporation. As a consequence, a reduced rate of convective overturning could cope with the marginally more active water cycle.

The convection overturning response identified in the GCMs, however, is in contrast to the tropical observations of Chen *et al.* (2002), who identified a decadal strengthening of the Hadley and Walker Circulations during the warming period of the 1990s. The surface warming generated increased convective instability as reflected in the responses of the two major overturning circulations driven by buoyancy forces.

Analyzing the same GCMs, Richter and Xie (2008) conclude there were three reasons for the rather slow rate of increase in evaporation as temperature increased: (1) an increase in boundary layer stability, (2) a reduction in surface wind speed, and (3) an increase in boundary layer relative humidity. These are surprising findings that suggest

in the models, as carbon dioxide concentration increases, the impact on convective instability from reduction in tropospheric radiation cooling overwhelms the increase in convective instability from reduction in net surface infrared radiation loss. The reduction in convective instability is realized as an increase in both boundary layer stability and boundary layer relative humidity, each tending to dampen the rate of increase in evaporation with temperature.

Therefore, after more than four decades of technological evolution in investigating the sensitivity of Earth's climate to increasing carbon dioxide concentration, there remains much uncertainty. The earliest simple surface energy balance models gave very low sensitivity because the reduction in net surface infrared radiation loss as carbon dioxide increased was offset largely by heat and moisture flux that damped surface temperature increase. The more sophisticated radiation/convection models did not discriminate between sensible and latent heat loss and the approximately 2°C temperature rise for doubling of carbon dioxide concentration was considered realistic. Contemporary high-resolution models with a complex representation of physics are even more sensitive to carbon dioxide forcing, but the clear suppression of surface evaporation increase with temperature possibly accounts for the heightened sensitivity.

This history in climate sensitivity makes clear there remain uncertainties with respect to how the interaction between increasing carbon dioxide concentration and Earth's infrared radiation fluxes should be incorporated in complex GCMs. Also key to determining climate sensitivity is the response of the water cycle as the energy exchange processes within the climate system respond. The early simple, albeit flawed, surface energy balance models point to an enhanced water cycle damping the surface temperature sensitivity to carbon dioxide forcing. This unresolved, elemental physics portrayal of the climate system does not lend confidence to current GCM projections under increasing carbon dioxide concentration.

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1.1.5 Climate Sensitivity

The “sensitivity” of temperature to carbon dioxide, which is the amount of total warming for a nominal doubling of atmospheric carbon dioxide, is the core parameter that ultimately drives global warming policy, and its magnitude has been the subject of a vigorous debate between scientists. The current draft of the United Nations’ Intergovernmental Panel on

Global Climate Models and Their Limitations

Climate Change AR5 report gives a mean model sensitivity of 3.4°C, and calculations from standard deviation tables given in the draft yield a 90% (5–95%) range of 2.1–4.7°C. As can be seen in Figure 1.1.5.1, these figures are quite high in comparison to a number of prominent recent studies detailed below.

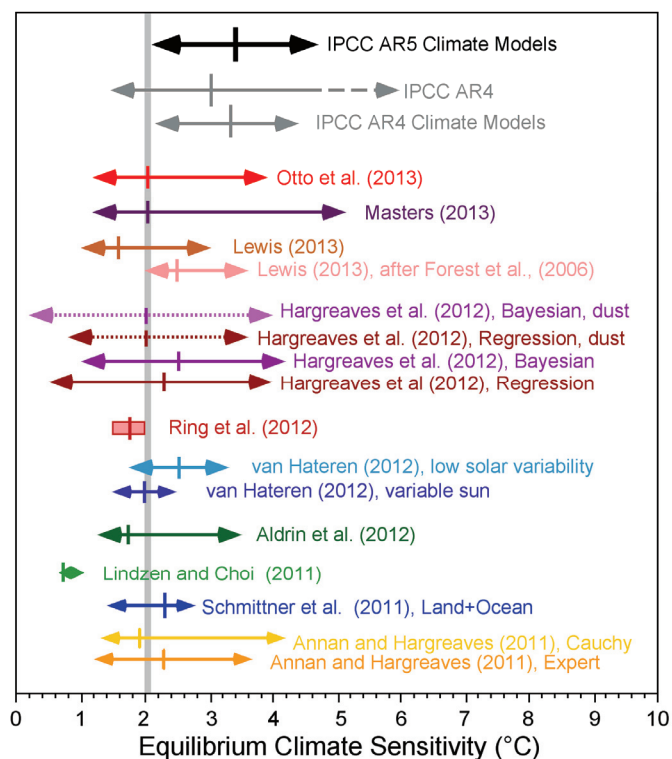


Figure 1.1.5.1. Climate sensitivity estimates from new research published since 2010 (colored, compared with the range given in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (gray) and the IPCC Fifth Assessment Report (AR5; black). The arrows indicate the 5 to 95% confidence bounds for each estimate along with the best estimate (median of each probability density function; or the mean of multiple estimates; colored vertical line). Ring et al. (2012) present four estimates of the climate sensitivity and the red box encompasses those estimates. The right-hand side of the IPCC AR4 range is dotted to indicate that the IPCC does not actually state the value for the upper 95% confidence bound of their estimate and the left-hand arrow only extends to the 10% lower bound as the 5% lower bound is not given. The light grey vertical bar is the mean of the 16 estimates from the new findings. The mean climate sensitivity (3.4°C) of the climate models used in the IPCC AR5 is 13 percent greater than the IPCC’s “best estimate” of 3.0°C and 70% greater than the mean of recent estimates (2.0°C).

NASA Senior Scientist David Rind of the Goddard Institute for Space Studies subtitled a recent paper, “We still can’t predict future climate responses

at low and high latitudes, which constrains our ability to forecast changes in atmospheric dynamics and regional climate” (Rind, 2008). Rind began his review and analysis of this important subject by noting Charney *et al.* (1979) concluded global temperature sensitivity to a doubling of the atmosphere’s CO₂ concentration was “between 1.5° and 4.5°C,” while noting since then “we have not moved very far from that range.” In addition, Rind reported the uncertainty in our assessment of high- and low-latitude climate sensitivity “is also still as great as ever, with a factor of 2 at both high and low latitudes.”

Rind identified several problems contributing to the uncertainty. Whether the water vapor response to warming employed by climate models “is realistic is hard to assess,” he noted, “because we have not had recent climate changes of the magnitude forecast for the rest of this century” to test against. Closely associated are low-latitude difficulties related to modeling both low- and high-level clouds in the tropics and the physics and dynamics associated with them, plus high-latitude difficulties associated with cryosphere feedbacks related to sea ice and snow cover.

One way of dealing with these uncertainties has been to suggest, in Rind’s words, that “we can have greater confidence in the multi-model mean changes than in that of any individual model for climate change assessments.” However, he writes, “it is doubtful that averaging different formulations together will end up giving the ‘right’ result,” because “model responses (e.g., tropical land precipitation) can often be of different signs, and there can be little confidence that averaging them together will produce a better result.”

Rind thus concludes, “at this point, we cannot determine the low- and high-latitude sensitivities, and we have no real way of obtaining them.” These unknowns, in his opinion, “affect the confidence we can have in many of our projections of atmospheric dynamic and hydrologic responses to global warming.”

Because of these and a host of other complexities he discusses, Rind states, “forecasting even the large-scale response to climate change is not easy given the current uncertainties” and “regional responses may be the end result of varying influences in part due to warming in different tropical and high-latitude regions.”

Rind concludes “real progress will be the result of continued and newer observations along with

modeling improvements based on these observations,” which observations must provide the basis for evaluating all model implications. So difficult is this task, however, that he says “there is no guarantee that these issues will be resolved before a substantial global warming impact is upon us.” There is, of course, also no guarantee there even will be any “substantial global warming impact” from a doubling or more of the air’s CO₂ content.

Lindzen and Choi (2009), two Massachusetts Institute of Technology scientists, used the National Centers for Environmental Prediction’s 16-year (1985–1999) monthly record of sea surface temperature (SST), together with corresponding radiation data from the Earth Radiation Budget Experiment, to estimate the sign and magnitude of climate feedback over the oceanic portion of the tropics and thus obtain an empirical evaluation of Earth’s thermal sensitivity, as opposed to the model-based evaluation employed by the IPCC.

The scientists found all 11 models employed in the IPCC’s analysis “agree as to positive feedback,” but they all *disagree*—and disagree “very sharply”—with the real-world observations Lindzen and Choi utilized, implying negative feedback actually prevails. Moreover, the presence of that negative feedback reduced the CO₂-induced propensity for warming to the extent that their analysis of the real-world observational data yielded only a mean SST increase “of ~0.5°C for a doubling of CO₂.”

Lindzen and Choi (2009) were criticized for not using available tropical high-altitude radiation data and for constraining feedback to within the tropics, which is highly unrealistic for a number of reasons, including Hadley Cell-westerly interactions and the export of large amounts of energy from the tropics into the temperate zone via tropical cyclones and poleward currents. They also did not explicitly use the IPCC-defined climate sensitivity.

However, Lindzen and Choi (2011) addressed these concerns by adding data from NASA’s Cloud and Earth Radiant Energy System (CERES), rather than simply using the older Earth Radiation Budget Experiment (ERBE) data. They also shared radiation feedback fluxes with the extratropics and addressed the sensitivity issues. The derived mean sensitivity was 0.7°, with a 90% range of 0.6–1.0°C, indicating virtually no positive amplification of warming beyond that from CO₂.

Another empirically based analysis of climate sensitivity was published several years earlier in the review paper of Idso (1998), who described eight

“natural experiments” he personally employed in prior studies designed to determine “how Earth’s near-surface air temperature responds to surface radiative perturbations.” The eight naturally occurring phenomena employed by Idso were (1) the change in the air’s water vapor content that occurs at Phoenix, Arizona, with the advent of the summer monsoon, (2) the naturally occurring vertical redistribution of dust that occurs at Phoenix between summer and winter, (3) the annual cycle of surface air temperature caused by the annual cycle of solar radiation absorption at Earth’s surface, (4) the warming effect of the entire atmosphere caused by its mean flux of thermal radiation to the surface of Earth, (5) the annually averaged equator-to-pole air temperature gradient sustained by the annually averaged equator-to-pole gradient of total surface-absorbed radiant energy, (6) the mean surface temperatures of Earth, Mars, and Venus relative to the amounts of CO₂ contained in their respective atmospheres, (7) the paradox of the faint early Sun and its implications for Earth’s thermal history, and (8) the greenhouse effect of water vapor over the tropical oceans and its impact on sea surface temperatures.

These eight analyses, Idso writes, suggest “a 300 to 600 ppm doubling of the atmosphere’s CO₂ concentration could raise the planet’s mean surface air temperature by only about 0.4°C,” in line with Lindzen and Choi’s deduced warming of ~0.5°C for a nominal doubling of the air’s CO₂ content. There would thus appear to be strong real-world data that argue against the order of magnitude larger CO₂ sensitivity predicted by state-of-the-art climate models.

Feedbacks are a natural part of the complexity of our climate system. They represent nonlinear processes within a system that are the result of the interaction between two or more variables or the interaction of a variable with itself (or its changes—“self” interaction) and influence overall climate sensitivity. Generally, these processes can only be parameterized, or represented in the models in an empirical way. Because of the inability to precisely represent feedbacks in a model, the model output may not be reasonable.

Temperature change in the climate system can be represented simply as a “forced-dissipative” relationship, for example by non-radiative and radiative processes as well as a net radiative restoring force, which is the feedback. As an example of this feedback process, if the system warms radiatively or non-radiatively, then the net radiative force may

become negative (longwave-out increases and becomes larger than shortwave-in). Thus, the net radiative force will act to counter the warming, and a larger restoring force would represent a less-sensitive climate. The opposite can be argued for the system cooling. These principles can be represented by a simple differential or mathematical equation.

Investigating this subject further, a paper by Spencer and Braswell (2011) explored the sensitivity of the surface temperature response to a forced radiative imbalance. They used observed shortwave and longwave radiation gathered from satellite measurements and calculated the net atmospheric radiation. They also used observed surface temperatures from the years 2000–2010 around the globe and calculated global monthly temperature anomalies relative to the average over the ten-year period. Using these two time series, they correlated one versus the other using different time lags and compared these observed values to the same variables gathered from the twentieth century runs of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) phase 3 multi-model data set. The authors chose the three most- and least-sensitive model runs, rather than using all of them. They also used the observed and modeled data to investigate the mathematical relationship for temperature change described above.

When Spencer and Braswell set a “feedback” parameter as described above, they demonstrated that only for pure non-radiative forcing and with no time lag can the parameter be accurately diagnosed in the model (see Figure 1.1.5.2). With radiative forcing and a 70/30% mix of radiative versus non-radiative forcing, the response was quite different: “in this case, radiative gain precedes, and radiative loss follows a temperature maximum, as would be expected based upon conservation of energy considerations.” They also found, more importantly, that the pure radiative forcing curve in Figure 1.1.5.2 looks more like one produced using the data from the climate models, while the mixed curve looks more like that produced using the observed data.

Spencer and Braswell then point out, “we are still faced with a rather large discrepancy in the time-lagged regression coefficients between the radiative signatures displayed in the real climate system in satellite data versus the climate models.” Such discrepancy indicates the climate system possesses less sensitivity than the climate models project. That is, climate models may overestimate the temperature change forced by a certain process (e.g., increasing

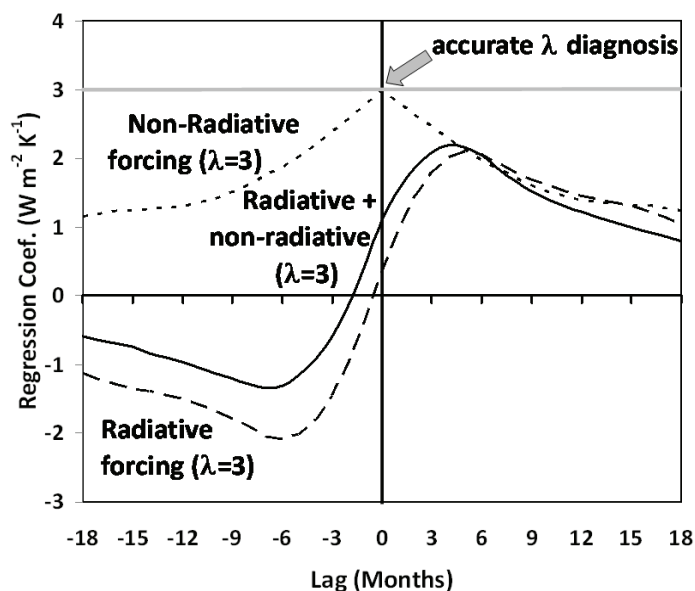


Figure 1.1.5.2. The lag regression coefficients between temperature (K) and radiative flux ($\text{W m}^{-2} \text{K}^{-1}$) for the case of (a) non radiative forcing (dotted line), (b) pure radiative forcing (dashed line), and (c) a 70/30% mixture of radiative and non-radiative forcing. Adapted from Spencer, R.W. and Braswell, W.D. 2011. On the misdiagnosis of surface temperature feedbacks from variations in Earth’s radiant energy balance. *Remote Sensing* 3: 1603–1613, Figure 4.

atmospheric CO_2).

Further, it should be noted Earth’s climate is a complicated dynamic system in which each part has characteristic time- and space-scales over which it evolves, or as it reacts to a forcing that is external to that part of system or to the system as a whole. The atmosphere, being less massive than the ocean or the cryosphere, tends to respond more rapidly than the other parts of the system. Thus, when the climate of the atmosphere by itself is modeled, we consider the atmosphere a boundary value problem; the atmosphere will be a servant to the underlying surface. It is often stated that the oceans, with their greater mass and higher thermal capacity, are the inertial and thermal flywheels of the climate system.

A number of recent papers have eliminated the feared “fat tail” of a reasonably finite probability of very large warming and reduced or median estimates.

Annan and Hargreaves (2011) adjusted Bayesian probability estimates of the range of sensitivity based upon analysis of their sensitivity to the choice of prior and recent ERBE data. They determined a sensitivity of $1.2\text{--}3.6^\circ\text{C}$, with a most likely value of 2.2° , which also eliminated the long “long fat tail” they note is “characteristic of all recent estimates of climate

sensitivity.” A Cauchy-derived probability gave 1.3–4.2°C, with a quite low 1.9° at $p=0.5$.

Also using a Bayesian approach, Schmittner *et al.* (2011) created an empirical-dynamic combination of land and ocean temperature reconstructions during the last glacial maximum combined with climate model simulations. Both eliminated the “fat tail,” with a probability density function (PDF) showing a “vanishing” probability below 1.0°C and above 3.2°C, and a 90% range of from 1.4–2.8°C. What is rather remarkable in this paper is how tightly constrained the PDF becomes when “real world” (interglacial/glacial) data are used, as the 66% range is not much smaller than the 90%, at 1.7–2.6°C, a net range change of only 0.5°C.

Aldrin *et al.* (2011) used a rather simple energy balance model to determine hemispheric surface temperature and global ocean heat content as a function of the estimated changes in radiative forcing. They derived a 90% range of 1.2–3.5°C, with a $p=0.5$ value of approximately 1.75°. Again using a single-average Earth temperature as the predictand, van Hatteren (2012) calculated an equilibrium sensitivity 90% confidence range of 1.7–2.3°C. Notably, the fit to the observed temperature rise in the past two centuries was significantly worse (and more warming was predicted) when van Hatteren’s solar variability parameter was reduced by an order of magnitude.

Ring *et al.* (2012) did not calculate a sensitivity range, but rather estimated equilibrium warming with a spectral decomposition model of the four main global temperature data sets, fit to long-lived greenhouse gases, compensating aerosols, changes in tropospheric ozone and land use, solar irradiance, and volcanic activity in a model estimating land and ocean temperatures, with a 40-layer oceanic model to allow for latitudinal advection of heat. Their equilibrium temperature change ranged from 1.5 to 2.0°C, and they noted

.... These are on the low end of the estimates in the IPCC’s *Fourth Assessment Report*. [1] So, while we find that most of the observed warming is due to human emissions of [long-lived greenhouse gases], future warming based on these estimations will grow more slowly than that under the IPCC’s “likely” range of climate sensitivity, from 2.0°C to 4.5°.

Notably, the fourth author of this paper, University of Illinois climate modeler Michael Schlesinger, has been one of the most outspoken

advocates of stringent and immediate controls of greenhouse emissions and, in earlier work, he had produced some of the largest estimates of equilibrium warming from carbon dioxide.

Using both posterior (regression) and prior (Bayesian) approaches, Hargreaves *et al.* (2012) calculated the sensitivity with models that either included or excluded atmospheric dust, where these approaches were coupled to seven common General Circulation Models (GCMs). The dust-free Bayesian model had the greatest sensitivity, with a range of 1.0–4.2°, with a central estimate of 2.4°C. The dust-included regression model yielded the smallest warming, a range of 0.8–3.4°C, with a central estimate of 2.0°C. The Bayesian dust-included model had a similar central estimate. Perhaps more important, Hargreaves *et al.* noted their collection of models yielded “a high probability of [equilibrium warming] lying below 4°C.”

Again coupling a Bayesian approach to a model, this time the MIT two-dimensional model, Lewis (2013) generated a 90% range of 1.0–3.0°C, with a central value of 1.6°C. Masters (2013) is the only recent sensitivity analysis based upon observed values of oceanic heat uptake, and he found a 90% sensitivity range of 1.2–5.1°, with a central value again of 2.0°C, substantially below what is in the suite of models employed in the existing draft of the IPCC’s *Fifth Assessment Report*.

Scaling the relationship between observed temperature in the widely cited HadCRUT4 temperature history with calculated changes in the total heat content of the Earth system, Otto *et al.* (2013) state their most reliable calculation yields a range of 1.2–3.9°C, centered on 2.0°C. The analogous range for the upcoming IPCC report is 2.2–4.7°C, centered on 3.4°C. This paper was authored by 17 very prominent climate scientists.

Many of the sensitivity values are very similar to the twenty-first century warming Michaels *et al.* (2002) had projected some ten years earlier based largely on observational data, which may be the first of the low-sensitivity data-based papers in the literature.

In total, there are 42 researchers describing 19 separate experiments in this section.

In another paper, Olivé *et al.* (2012) examined the changes in global temperature relative to changes in CO₂ concentration using two different models. This study also endeavored to quantify the uncertainties in the authors’ scenarios. The authors used output from the Hadley Centre’s Atmosphere-Ocean (UKMO-

HadCM3) and the CNRM-CM3 Centre National de Recherches Meteorologiques Coupled Model, version 3 (CNRM-CM3) coupled Atmosphere Ocean General Circulation Models (AOGCMs). The simulations were relatively short, on the time scale of 100 to 300 years, since the model spatial resolution was higher. The authors also used CO₂ scenarios where the increase was simulated to be sudden, corresponding to a 6.5 times increase (10 W/m²), a sudden doubling, and then a gradual increase. The gradual increases (1% per year) resulted in a doubling and quadrupling of CO₂ in 70 and 140 years, respectively. Additionally, the authors initially used a shorter (10 years) and long-scale (100 years) CO₂ forcing as well as sensitivity values within the range of those given in the published literature for their *a priori* estimates. Then they solved the equations backward to get their estimates of the short- and long-time-scale modes and sensitivity.

The results from Olivé *et al.* (2012) show the short-time-scale temperature forcing for CO₂ was on the order of three to four years, while it was 100 to 300 years on the long-time-scale. The shorter mode of temperature change was faster for the model simulations where the CO₂ forcing was sudden (Figure 1.1.5.3) rather than the gradual CO₂ increase simulations. The uncertainty also was lower for the sudden increase simulations. For the longer time-scale forcing, longer model integrations would be needed to estimate these and reduce the uncertainty. Concerning the model sensitivities, the authors write, “when assuming two modes it varies between 0.49 and 0.83 K W⁻¹ m² or between 0.56 and 1.01 K W⁻¹ m²,” both within the published range shown early in the paper.

This kind of diagnostic work is an important use of long-term computer model simulations. Even though there is no predictive work being done in this study, it is remarkable that there is such variation in the estimate of the short- and long-term radiative forcing as well as in the climate sensitivity. This is especially true between the two models used. Such findings demonstrate the models are less than perfect, as any of these internal differences would have to be the result of the model physics employed, especially that pertaining to radiative forcing. Also, such long integrations should lead to the build-up of numerical errors. Lastly, the fact that the authors could not appreciably reduce the uncertainty in estimating these quantities indicates further improvement is not likely using the current technology.

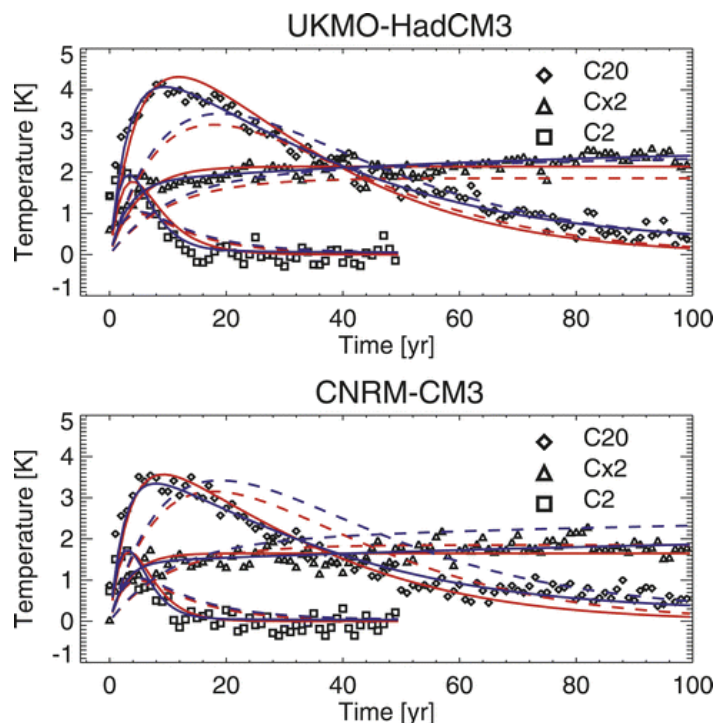


Figure 1.1.5.3. A time series of global- and annual-mean surface air temperature obtained with a one (red line) and two (blue line) mode approach for (top) UKMO-HadCM3 and (bottom) CNRM-CM3. The model data are represented by the symbols, and the modal results obtained using a priori (a posteriori) parameter values are represented by the dashed (solid) lines. C20 and Cx2 represent scenarios with increased atmospheric CO₂ in a stepwise fashion (Cx2 is slower). The C2 scenario represents a sudden doubling of CO₂. Adapted from Olivé, D.J.L., Peters, G.P., and Saint-Martin, D. 2012. Atmosphere Response Time Scales Estimated from AOGCM Experiments. *Journal of Climate* **25**: 7956–7972, Figure 1.

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1.1.6 Climate Response and Projection

Climate change can occur due to internal variations in the system or internal forcing, the interaction among properties or parts of the climate system with each other. Climate also can be forced externally, influenced by phenomena considered to be outside the climate system, such as volcanic action, solar forcing, or an “artificial” disturbance such as that imposed by human-emitted greenhouse gases.

The IPCC used GCMs to make two claims about anthropogenic climate warming. The first is that most or all of the warming occurring during the latter part of the twentieth century was human-induced. In its *Fourth Assessment Report* (AR4), the IPCC asserts anthropogenic forcing dominates natural forcing. Yet even in AR4 (Chapter 2), the IPCC admits low confidence in its knowledge of the size of solar forcing since 1750. By contrast, the Nongovernmental International Panel on Climate Change (NIPCC, 2009) has demonstrated a strong correlation between, for example, solar variations and global temperature (see also Chapter 3 of this volume). The second claim made by the IPCC in AR4 is that by the end of the twenty-first century, a warming of 1.0 °C to 3.6 °C or more will have occurred due to human activity.

The IPCC's assertion of the dominance of anthropogenic forcing is merely that: an assertion. Decades ago, Leith (1975) used the fluctuation-dissipation (F-D) theorem from statistical mechanics to study “the way in which a climate mean would return to its original value after it had been artificially perturbed.” In his short paper he proved the theorem mathematically and then applied it to the problem of using climate models to create climate change scenarios. In his proof of the F-D theorem, Leith demonstrated that as long as the conditions for the theorem hold, the mean dissipation of a fluctuation (or disturbance) is that projected by a linear regression (statistical) model. It would not matter whether the disturbance was artificial or natural, just that they be small and of similar size. Leith acknowledged the character of the climate system may not be such that the F-D theorem holds exactly, but studies in turbulence show it is a reasonable approximation for its behavior.

One implication is that it is difficult to ascribe temperature change to one process if two or more processes causing the temperature change are of similar magnitude. Moreover, if it is assumed that an artificial forcing is much greater than a natural forcing, as does the IPCC, then the GCMs will generate climate responses much larger than those of

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natural variability. Lastly, the F-D theorem implies the use of complex GCMs will not necessarily project future conditions any better than a statistical model.

The fact that observed global temperature increases in the instrumental record since the late 1800s do not show rates of change sufficiently larger, or even different from, those implied in the proxies for the last one to two millennia (Figure 1.1.6.1; see also Chapter 4) does not bode positively for the IPCC's assumption that human forcing is the dominant player in climate change. Even a further warming (of about 0.6°C or less) by 2100, as predicted by the IPCC, does not necessarily imply an anthropogenic origin.

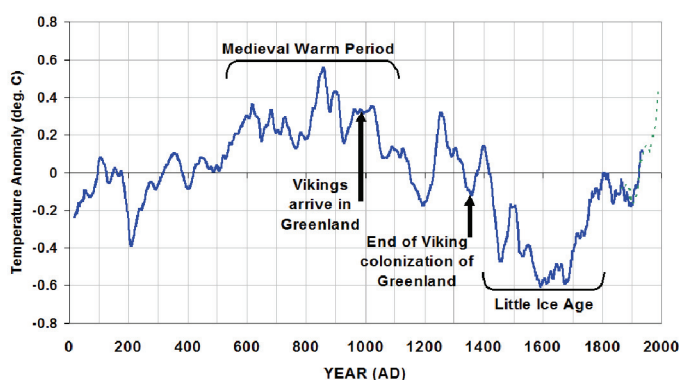


Figure 1.1.6.1. The estimate of global temperature change for the past 2,000 years (2 KY) in degrees centigrade. Adapted from Spencer, R., 2013, <http://www.drroyspencer.com/latest-global-temperatures/>.

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1.1.7 Regional Projection

Some observers of the climate change debate, scientists and non-scientists alike, have criticized the efforts to model future climate by asking how projections 100 years into the future can be made when a weather model can't get this weekend's weather right. Modeling is a complicated process, and weather forecasting and climate projection are two

very different problems that require different strategies.

Weather forecasting can be done dynamically, by (a) taking the mathematics and physics that represent the atmosphere, (b) initializing with a clean set of measurements, and (c) running a computer program forward, generating a forecast that in theory represents the atmosphere at a certain prediction time. However, as noted earlier, such predictions can be calculated for only about 10 to 14 days into the future.

Climate projection (as opposed to weather prediction) relies on the assumption that the statistics generated after lengthy simulations (years or decades) would adequately represent the climate of some future period. The focus of climate projections is to replicate the energy flows within the climate system such that any accumulation or decrease represents real changes due either to internal redistribution of energy or imbalances in the radiation exchange to space.

The basis for confidence in the anthropogenic global warming hypothesis is that changes in atmospheric carbon dioxide concentration introduce a bias in the exchange of radiation energy with space. As the boundary energy exchanges slowly change, there is a concomitant movement of internal indices, such as global surface temperature, that can be modeled. Such projections require additional physics and tighter constraints on the magnitudes of internal energy exchanges than those utilized in weather forecasting models. For example, changing aerosol forcing from natural or human sources would have a negligible effect on the prediction of weekend weather, but over the course of many years can have a large impact on regional or global climate.

In a recent paper, Liang *et al.* (2012) examined the feasibility of converting the Weather Research and Forecasting model (WRF) into a regional climate model (CWRF). In doing so, they noted “there has been some success using the WRF for regional climate downscaling,” adding that “such direct applications, however, also have encountered numerous problems.”

In order to convert the WRF for climate projections, the authors acknowledged the need for the use of cloud aerosol and radiation physics more common to climate models. Also, atmospheric “communication” with the oceans and land (exchanges of heat, moisture, and momentum) needed to be upgraded to deal with boundary value problems. Additionally, the horizontal and vertical resolutions used were the same as those for weather forecasting,

30 km in the horizontal and 36 vertical levels (although weather forecasting can be done at finer resolutions). The model focused on the United States and adjacent regions, and the authors attempted to replicate the climate of the most recent decades and compared their results to observations and those produced by another climate model.

The CWRf generally improved the simulation of the geographical distribution and seasonal/interannual variability of such quantities as precipitation, surface temperature, and downwelling radiation, although not for all regions and seasons. The authors acknowledge “accurate simulation of precipitation in all seasons and regions remains a challenge for all of the tested models.” Nonetheless, this initial test proved successful to the satisfaction of the authors, justifying more testing and release of the model to the public.

The CWRf’s performance was not universally superior (see Figure 1.1.7.1). For example, used with different physics packages to project the great Mississippi River Basin flooding of 1993, the CWRf demonstrated limited skill. However, for seasonal rainfall rates, there was enhanced skill when the projections were averaged. While this modeling system represents an improvement over others in some respects and is another tool for modelers to use, climate modeling remains an inexact science far from being able to show us the climate of some distant future.

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1.1.8 Seasonal Projection

Climate models are tested and reworked with the goal of developing ever-more-accurate representations of how the real world operates, so as to be able to make confident projections of Earth’s future climate.

Kim *et al.* (2012) write, “the seasonal prediction skill for the Northern Hemisphere winter [was] assessed using retrospective predictions (1982–2010) from the ECMWF System 4 (Sys4) and [the] National Center for Environmental Prediction (NCEP) CFS version 2 (CFSv2) coupled atmosphere-ocean seasonal climate prediction systems.” The analysis revealed “for the Sys4, a cold bias is found across the

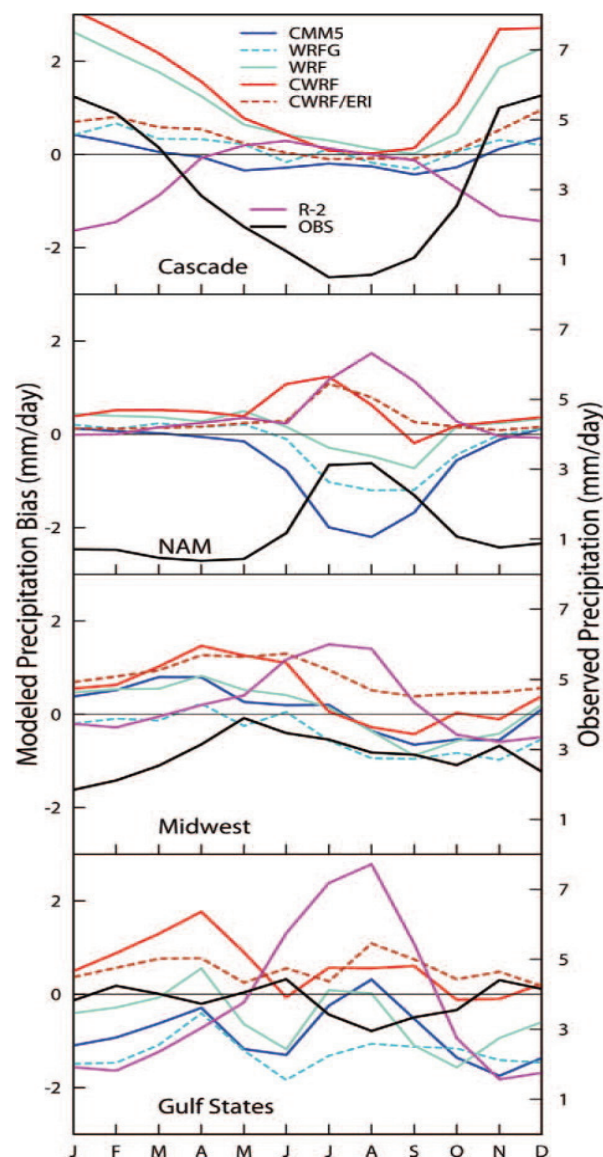


Figure 1.1.7.1. The 1982–2004 mean annual cycle of precipitation biases (mm day^{-1} , left hand scale) simulated by the models, and the observed precipitation (mm day^{-1} , right hand scale) averaged over the four key regions. Also shown are the CWRf/ERI biases averaged during 1990–2008. The zero line only pertains to the left axis. Reprinted with permission from Liang, X.Z., Xu, M., Yuan, X., Ling, T., Choi, H.I., Zhang, F., Chen, L., Liu, S., Su, S., Qiao, F., He, Y., Wang, J.X.L., Kunkel, K.E., Gao, W., Joseph, E.E., Morris, V., Yu, T.-W., Dudhia, J., and Michalakes, J. 2012. Regional climate-weather research and forecasting model. *Bulletin of the American Meteorological Society* **93**: 1363–1380, Figure 4.

equatorial Pacific”; “the CFSv2 has [a] strong warm bias from the cold tongue region of the Pacific to the equatorial central Pacific and [a] bias in broad areas of the North Pacific and the North Atlantic.”

The researchers also found, “a cold bias over large regions of the Southern Hemisphere is a common property of both reforecasts”; “with respect to precipitation, the Sys4 produced excesses along the Intertropical Convergence Zone, the equatorial Indian Ocean and the western Pacific”; “in the CFSv2, a strong wet bias is found along the South Pacific Convergence Zone and the southern Indian Ocean, as well as in the western Pacific”; “a dry bias is found for both modeling systems over South America and northern Australia and wet bias[es] in East Asia and the equatorial Atlantic”; and “both models have difficulty in forecasting the North Atlantic Oscillation and the year-to-year winter temperature variability over North America and northern Europe.”

Reference

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1.2 Modeling Techniques

Researchers are improving the ability of GCMs to simulate the large-scale climate and its interannual variability. However, the models still cannot adequately simulate phenomena that arise from smaller-scale processes such as precipitation, even in areas where precipitation is quite frequent, such as the East Asian Monsoon region. Efforts are continually being made to improve the portrayal of regional climates, model physics and parameterizations, and even the representations of the equations themselves. This section describes some of the studies exploring the subject of model improvement.

1.2.1 Downscaling

One technique developed to improve model performance is called downscaling, a process by which a regional climate model is used over a limited area but with a higher resolution, allowing smaller-scale atmospheric processes to be represented more faithfully, giving the regional climate scenario a finer structure. Downscaling allows an examination of model performance (validation) and a look at the finer-scale details of the projections (e.g. Christensen *et al.* 2007).

One limitation of this technique, however, is that each of the lower-resolution errors and scale-

matching at the grid boundary travel to the interior of the finer-resolution portion of the grid and, to some degree, confound the outcome. Given the short time for these errors to propagate inwards and the long duration of climate simulations, this is an unresolved problem that must be addressed.

Zou *et al.* (2010) sought to determine whether downscaling can improve a GCM’s ability to replicate the climatology of East Asian Monsoon precipitation. The authors used the LMDz4 model from the Laboratoire de Meteorologie Dynamique in France. This GCM can be run with a coarse grid (1.125 degrees latitude and longitude, or roughly 125 km) or it can be run in “zoom” mode such that the regional area has a grid resolution of about 50 km. The regional simulation has a grid resolution similar to that of a weather forecast model.

Zou *et al.* ran the model for the East Asia Region for the years 1958–2000 in order to compare the modeled climate to monthly observations from this region over the same time period. The raw output revealed the model produced more (less) precipitation when downscaling was (not) used. When the authors extracted the larger-scale component of the precipitation signal from the precipitation data (Figure 1.2.1.1), they found the model results without downscaling were unable to adequately represent the monsoon pattern or its variability (compare Figure 1.2.1.1 frames a, b to frames e, f). The downscaling results (Figure 1.2.1.1 frames c, d) compared more favorably.

Even though the results were an improvement, flaws remained. As Zou *et al.* point out, “it should be acknowledged that our results of dynamic downscaling are not perfect,” while adding “the main weakness of the downscaling is the northward shift of the monsoon rainbelt.” Although downscaling improves some aspects of the performance of models and their ability to represent observations, this technique is still subject to the general limitations suffered by all numerical models.

Indeed, numerous errors permeate numerical models for both weather forecasts and climate projections. These fall under three headings, (1) observational error, (2) numerical error, and (3) physical error.

Observational error refers to the fact that instrumentation cannot measure the state of the atmosphere with infinite precision; it is important both for establishing the initial conditions and validation. *Numerical error* covers many shortcomings including “aliasing,” the tendency to

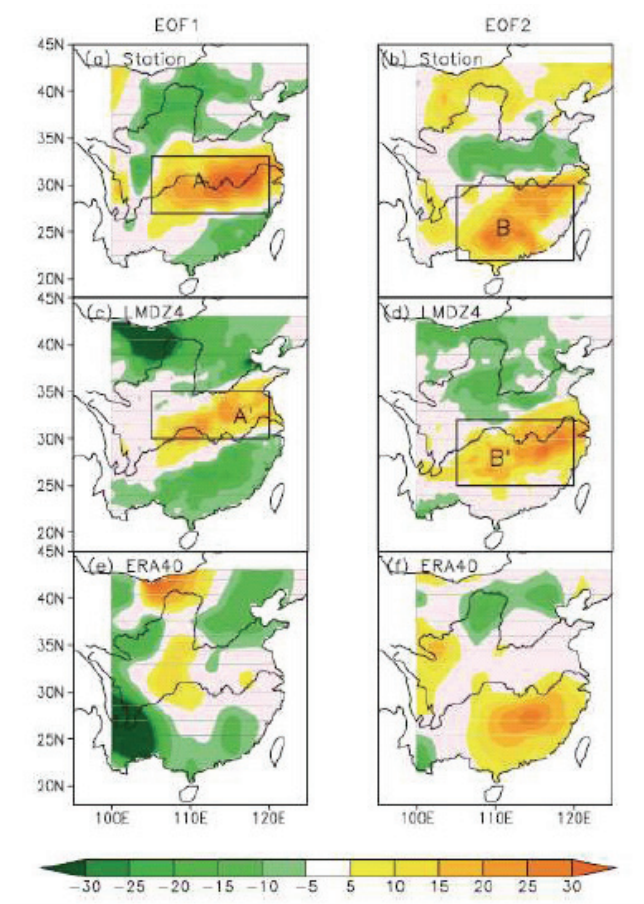


Figure 1.2.1.1. The strongest (left) and second strongest (right) component of summer season precipitation shown as a percentage from the rain gauge observations (top), the GCM with downscaling (middle), and the GCM without downscaling (bottom). Darker (lighter) colors represent more (less) precipitation than the actual measurements. Reprinted with permission from Zou, L., Zhou, T., Li, L., and Zhang, J. 2010. East China summer rainfall variability of 1958–2000: Dynamical downscaling with a variable resolution AGCM. *Journal of Climate* **23**: 6394–6408, Figure 4.

misrepresent the sub-grid scale processes as larger-scale features. In the downscaling approach, presumably errors in the large-scale boundary conditions also will propagate into the nested grid. Also, the numerical methods themselves are only approximations to the solution of the mathematical equations, and this results in truncation error. *Physical errors* are manifest in parameterizations, which may be approximations, simplifications, or educated guesses about how real processes work. An example of this type of error would be the representation of cloud formation and dissipation in a

model, which is generally a crude approximation.

Each of these error sources generates and propagates errors in model simulations. Without some “interference” from model designers, model solutions accumulate energy at the smallest scales of resolution or blow up rapidly due to computational error. In weather prediction, techniques have been developed to “smooth” and massage the data during a simulation by removing as much grid-scale energy as possible while retaining the character of the larger scale. Nonetheless, computational error does prevent models from forecasting perfectly, and this explains why two different models (or even two different runs with the same model) can give two different answers given the same or similar set of initial conditions.

Otte *et al.* (2012) use a technique called “nudging” to improve the performance of a weather forecasting model (Weather Research and Forecasting model—WRF) for use in downscaling. Nudging is used to keep the regional model results within the bounds of the larger-scale model results.

Generally applied to the boundaries of a model, Otte *et al.* applied the nudging technique to the interior of the grids. To test the procedure, they used a coarse analysis data set from the National Centers for Environmental Prediction to initialize the regional model. These analyses stood as a proxy for GCM output. They then compared their results to two fine-scale regional re-analyses for North America.

This modeling technique generated a better representation of monthly means and improved interannual variability. The simulations of hot and cold extremes, as well as wet and dry extremes, were captured better in the nudged WRF. However, Otte *et al.* note, “all WRF runs overpredicted precipitation totals through the multidecadal period ... regardless of whether nudging was used” (see Figure 1.2.1.2). Fewer false alarms of severe precipitation events were produced with the nudging technique than when it was not used, an important result given that most impacts on society result from the occurrence of extreme events. Reliable simulations that include the realistic occurrence of extremes are valuable for economic planners.

In spite of the success of the nudging employed by Otte *et al.* (2012), their results demonstrate modeling today’s climate cannot be done either on the largest scales or regionally without some way of “tuning” the model. This entails using parametric means to force the model to adequately represent reality. Although downscaling can be a valuable tool for regional climate simulations, this newfound ability

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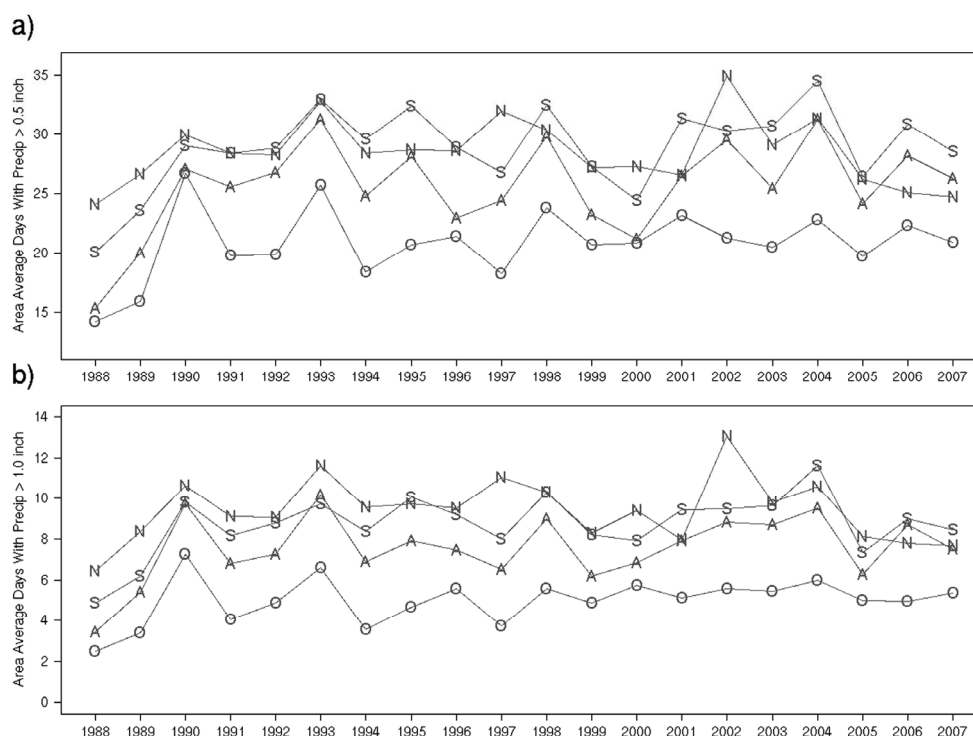


Figure 1.2.1.2. The annual area-averaged number of days with (a) precipitation greater than (a) 0.5 in, and (b) 1.0 in for the Midwest region. Data are shown from North American Regional Reanalyses (O) and WRF runs for no nudging (N), nudging toward analyses (A), and spectral nudging (S). Adapted from Otte, T.L., Nolte, C.G., Otte, M.J., and Bowden, J.H. 2012. Does nudging squelch the extremes in regional climate modeling? *Journal of Climate* **25**: 7046–7066, Figure 13.

is meaningless if the GCM results that are being downscaled are themselves unrealistic.

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Otte, T.L., Nolte, C.G., Otte, M.J., and Bowden, J.H. 2012. Does nudging squelch the extremes in regional climate modeling? *Journal of Climate* **25**: 7046–7066.

Zou, L., Zhou, T., Li, L., and Zhang, J. 2010. East China summer rainfall variability of 1958–2000: Dynamical downscaling with a variable resolution AGCM. *Journal of Climate* **23**: 6394–6408.

1.2.2 The Dynamic Core

An atmospheric model, whether a forecast model or one used to diagnose which processes drive the climate, is built on a foundation of three main conservation principles: Within the Earth-atmosphere system, mass, energy, and momentum must be conserved. These basic physical principles are represented by a closed set of equations termed the primitive equations. The equations form the “dynamic core” of climate models and represent the motions of air within the model. The model output is generally some variable representing mass (pressure), temperature, or both.

The primitive equations are too complex in their raw form to be represented adequately in models and are often simplified following the concept of Occam’s Razor: They are simplified as much as possible, and no more. One way these equations have been simplified is to “linearize” them, thereby eliminating nonlinearity that can make a computer model unstable. This nonlinearity is a process by which the atmosphere behaves in a chaotic fashion. It is also the reason computational errors propagate and amplify. The falsely generated energy interacts across all

scales of motion to distort the path of the model evolution such that eventually the scales of motion of interest (weather systems) have only limited forecast relationship to that of the atmosphere they are attempting to reproduce. This is the predictability barrier.

Kondrashov *et al.* (2011) used a simplified three-level atmospheric circulation model designed by Marshall and Molteni (1993) to show the evolution of the wind fields. The model has a fairly coarse horizontal and vertical resolution by today's standards, but it has been shown to represent the largest scales of the atmosphere's climate in a fairly realistic way. The experiment here examined the tendencies of the 500 hPa mass field (streamfunction) due to linear and nonlinear processes. The nonlinear processes were divided into those that are resolvable by the model and those that are of smaller scale than can be represented by the model.

The model output was slightly different depending on which processes were included in the model run. A comparison of the full nonlinear processes or interactions (Figure 1.2.2.1a) gave slightly different results than when comparing only nonlinear resolvable processes (Figure 1.2.2.1b). The

model output also differed from that of two similar studies because of the strategies used to calculate these model "climates." The authors conclude the article by stating "the manner of defining interactions between the resolved and unresolved modes plays a crucial role in the dynamical interpretation of the tendency-based statistical diagnostics."

The basic lesson to be learned from the authors' closing statement is that there can be output differences produced within the same model core even when using the same input data, depending on how the nonlinear processes are represented. If the representation of climate can be different depending on how these core processes are represented, then producing model scenarios on the time scale of a century must be done very cautiously and interpretation of the results done carefully.

References

Kondrashov, D., Kravtsov, S., and Ghil, M. 2011. Signatures of nonlinear dynamics in an idealized atmospheric model. *Journal of the Atmospheric Sciences* **68**: 3–12.

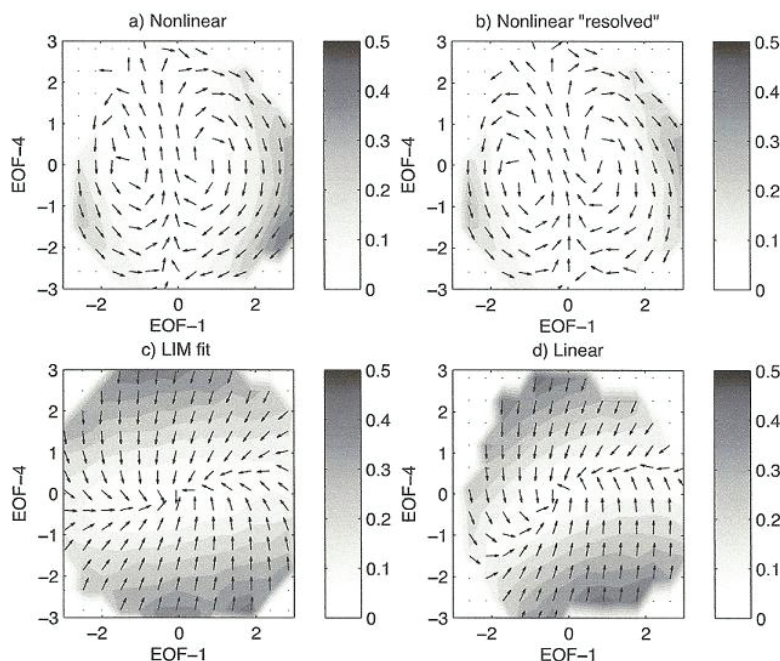


Figure 1.2.2.1. The mean tendencies (model output) in the phase space (mathematical space, not physical), for (a) tendencies due to the full nonlinear processes, (b) nonlinear processes that are resolvable, (c) the linear inverse model output, and (d) the linear part of the nonlinear tendencies. Adapted from Kondrashov, D., Kravtsov, S., and Ghil, M. 2011. Signatures of nonlinear dynamics in an idealized atmospheric model. *Journal of the Atmospheric Sciences* **68**: 3–12.

Marshall, J. and Molteni, F. 1993. Toward a dynamical understanding of atmospheric weather regimes. *Journal of the Atmospheric Sciences* **50**: 1972–1818.

1.2.3 Statistical Models

1.2.3.1 Statistical Validation

The Intertropical Convergence Zone (ITCZ) is an important feature in the atmosphere's general circulation. The ITCZ is a belt of low pressure near the equator where the northeast and southeast trade winds from the Northern and Southern Hemispheres converge. The ITCZ is also characterized by light winds and intermittent regions of convective activity. In some parts of the globe it is easy to identify and in other parts it is more difficult, as it is ill-defined.

This feature is important to the climate system because convection in the ITCZ is the vehicle by which the excess heat and momentum of the tropics begins the journey poleward so as to keep the energetics of the climate system in balance. The ITCZ, which migrates northward in the tropics from January to July (and back southward in July to January), is also an important contributor to the occurrence of the monsoons and often serves as the producer of seed disturbances that become tropical cyclones. Thus it would be important for any study of climate to be able to identify and understand the dynamics of this feature.

Bain *et al.* (2011) used satellite data to develop a modeling tool that can be used to objectively and reliably locate the ITCZ. They used images derived from reflected light (visible—VIS) and radiated energy (infrared images—IR) from Earth. They also used images generated by the intensity of microwave emission and measuring the return (water vapor depth—WV). They limited their domain to the Eastern Pacific from the International Dateline to South America, over the period 1995–2008.

In the model, the presence of the ITCZ was inferred based on the most likely location prior to analysis. Then a point was labeled as ITCZ or non-ITCZ by testing the value of the satellite data typical for the ITCZ, as well as the status of the surrounding grid points in both time and space. A second pass of the dataset blended the *a priori* information with the satellite data and the likelihood that a particular point was ITCZ or non-ITCZ. The method was then evaluated against manual observation and identification of the ITCZ (see Figure 1.2.3.1.1).

The statistical methodology of Bain *et al.* tested

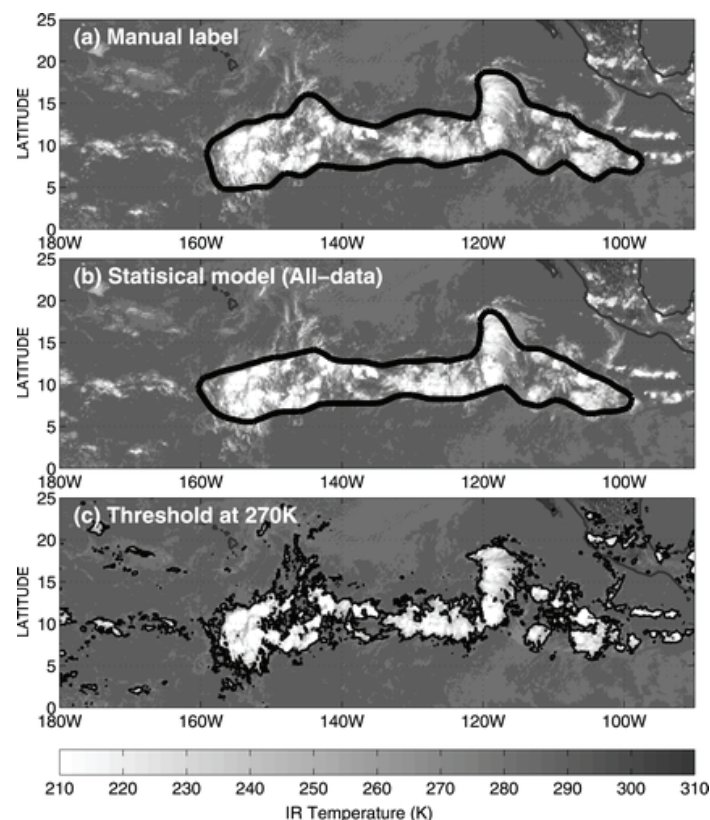


Figure 1.2.3.1.1. The ITCZ cloudiness for 2100 UTC 19 August 2000 overlaid on the IR data for (a) the manual detection, (b) the statistical model from the IR, VIS, and WV satellite data, and (c) the threshold at 270 Kelvin without post-processing. The gray-scale bar below represents the temperatures in the image, and the bold contour in (a) and (b) the position of the ITCZ. Adapted from Bain, C.L., J. DePaz, J. Kramer, G. Magnusdottir, P. Smyth, H. Stern, and C.-C. Wang, 2011. Detecting the ITCZ in instantaneous satellite data using spatiotemporal statistical modeling: ITCZ climatology in the East Pacific. *Journal of Climate* **24**: 216–230, Figure 3.

very well in objectively identifying the ITCZ and was subsequently used to examine the climatological characteristics of the ITCZ. The seasonal evolution of the ITCZ as determined by the methodology showed it migrated with the seasons and its passage followed the seasonal location for the regions of warm sea surface temperatures (SSTs). In order to look at the climatological trends and interannual variations, Bain *et al.* extended the satellite data set back to 1980 for the IR data only. In doing so they found there was enhanced (less) ITCZ convection in El Niño (La Niña) years, a finding reached in previous studies. However, they found “no climatic shifts in the position of the ITCZ could be detected,” which suggests, they write, “any trends in the ITCZ location

over the 30 years (that are not due to ENSO) are quite small or non-existent.”

Thus, statistical modeling can be used to objectively identify, in more detail, important features of the general circulation that we previously thought were well-known. The successful design of a model to objectively locate the ITCZ will be useful in the future study of its dynamics as well as its interaction with other tropical features such as the monsoons or the Madden Julian Oscillation (MJO), which manifests as a 30- to 60-day oscillation in tropical convection. Not all models are dynamic, and not all models are used to project the future climate. But using this particular model, Bain *et al.* showed no significant change in the character of the ITCZ in the past 30 years over the tropical Eastern Pacific.

Reference

Bain, C.L., J. DePaz, J. Kramer, G. Magnúsdóttir, P. Smyth, H. Stern, and C.-C. Wang, 2011. Detecting the ITCZ in instantaneous satellite data using spatiotemporal statistical modeling: ITCZ climatology in the East Pacific. *Journal of Climate* **24**: 216–230.

1.2.3.2 Empirical Models

Models can be analytical, statistical, or empirically derived and are then used to examine trends or cycles in a time series in an effort to determine the causes of change or variability.

Loehle and Scafetta (2011) built a one-dimensional model of global temperatures from 1850 to 2010 using the inductive approach and used this model to project the change in climate from the current time to the year 2100. The authors constructed their model using what they called “decomposition analysis,” based on a method of cycles and used in identifying cyclic behavior in a time series.

Previous research from each author and their colleagues had found there are cyclic and quasi-cyclic forcing processes that can be extracted from local and global time series of temperature. Such cycles can be related to solar and astronomical activity (for example 11, 22, 50–80 years; see Chapter 3 of this volume), or terrestrial oscillations such as the Pacific Decadal Oscillation (about 60 years). Their earlier research pointed to the presence and dominance of 20- and 60- year cycles in temperature time series. Their model also identified a linear trend that may be related to solar and volcanic activity since the middle of the Little Ice Age. Additionally, they

included an anthropogenic trend emerging in the early 1940s (Figure 1.2.3.2.1). These four processes combined to produce a model that fit the global temperature series from 1850 to 2010 very well.

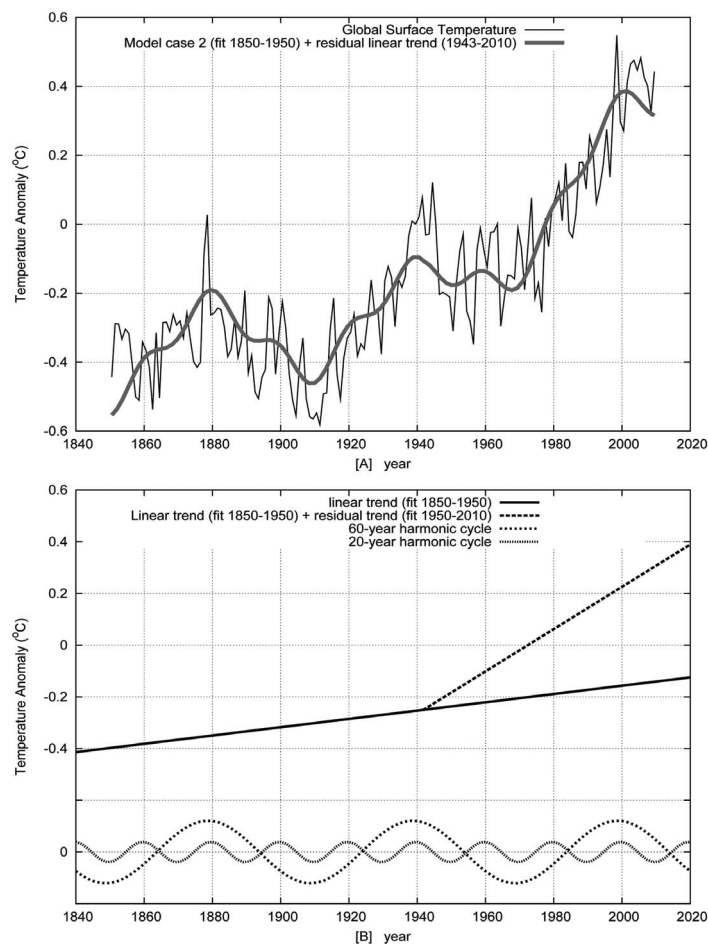


Figure 1.2.3.2.1. (Top) A full reconstruction of the global temperature anomaly (°C) record of 1850–2010 using the model described by Loehle and Scafetta (2011). (Bottom) The individual components of the model, where the solid line is the long term trend and the dashed line is the anthropogenic component. Adapted from Loehle, C. and Scafetta, N. 2011. Climate change attribution using empirical decomposition of climatic data. *The Open Atmospheric Science Journal* **5**: 74–86, Figure 3.

Loehle and Scafetta determined that more than 50 percent and as much as 60 percent of the climate signal from 1850 to 2010 was the product of natural forcing. They projected future climate to the year 2100 using the model, stating, “the result is a continued warming with oscillations to a high in 2100 of about 0.6°C above 2000 values.” This resulted from the combined effect of natural and anthropogenic forcing.

The 0.6°C temperature rise projected by the Loehle and Scafetta model is much less than the low-end estimates of 2.3°C projected by the GCMs relied upon by the IPCC and is consistent with recent estimates of low climate sensitivity. Also, the Loehle and Scafetta model shows the latest downturn in temperatures since 2000. The IPCC (2007) models do not show this downturn and assume 90 percent or more of the climate change since 1970 is anthropogenic. As Loehle and Scafetta point out, “we have shown that the effect of natural oscillations is critical for proper assessment of anthropogenic impacts on the climate system.” Perhaps this is why Loehle and Scafetta’s model fits the historic temperature data much better than do most of the IPCC models, and with far fewer parameters.

Several studies have shown GCMs are improving in their ability to reproduce the current climate, including intraseasonal and interannual variations. The ability of the GCMs to capture internal nonlinear processes, however, will always be suspect.

But when examining climate, important external forcing processes need to be accounted for, including such natural processes as volcanic activity and solar variations. There is increasing evidence that extraterrestrial forcing processes can have an impact on solar variations and, thus, terrestrial climate.

Recent work by Scafetta (2011) explores several such issues. First, the author expanded on his own work demonstrating a link between well-known climate cycles of roughly 10, 20, and 60 years to celestial cycles. The celestial cycles result from the solar-lunar tidal oscillation (9.1 years) and gravitational cycles related to the interaction between the sun and the largest planets (Jupiter and Saturn). These celestial cycles have periods of about 10, 20, and 60 years. Loehle and Scafetta (2011) demonstrated these cycles can be added together and, with a realistic anthropogenic effect, reconstruct the global climate record since 1950. They also show this empirical model can be used to project climate into the twenty-first century.

Scafetta also demonstrated the IPCC GCMs cannot capture decadal and interdecadal variability. As shown by the author (see Figure 1.2.3.2.2), “although these GCM simulations present some kind of red-noise variability supposed to simulate the multi-annual, decadal, and multidecadal natural variability, a simple visual comparison among the simulations and the temperature record gives a clear impression that the simulated variability has nothing to do with the observed temperature dynamics.”

Scafetta then demonstrates natural variability is not solely the result of internal variations; the external forcing described above also plays a role. These external forcings modulate solar output, which in turn impacts electrical activity in the upper atmosphere. This influences incoming cosmic ray fluxes, which have been linked to variability in cloudiness. The external cycles have periods similar to internal climate variations. Natural variations then, likely account for more than half the climate variability since 1850.

Finally, Scafetta also demonstrated the IPCC is erroneous in ascribing nearly all of the twentieth and twenty-first century climate change to anthropogenic forcing. When the anthropogenic effect is corrected, it accounts for less than half the recent climate change. Scafetta also showed his empirical model projected the cooling of the most recent decade, whereas the IPCC GCMs produced a quasi-monotonic warming of the climate from about the year 2000 on. Scafetta’s model produces a warming of only 0.8–1.5° C by the end of the twenty-first century.

Scientists skeptical of the IPCC’s projections of anthropogenic climate change have cautioned the public about the shortcomings of the IPCCs reliance on GCMs in producing climate change scenarios for the next century. In addition to well-documented problems with model numerics, the lack of data, and chaos, the physics of the models fall short. This is true not only for such internal processes as cloud physics, but also for such external forcing as Sun-moon tidal forcing and other solar system gravitational cycles that influence solar output.

Scafetta’s work demonstrates there is increasing evidence our solar system plays a significant role in decadal and multidecadal climate variations. The climate projections produced by Scafetta’s empirical harmonic model may be far more realistic and are certainly more optimistic.

References

IPCC. 2007. *Climate Change 2007 -I: The Science of Basis, Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K, Tignor, M.M.B., Miller, H.L. Jr., and Chen, Z.. Cambridge University Press, Cambridge, UK.

Loehle, C. and Scafetta, N. 2011. Climate change attribution using empirical decomposition of climatic data. *The Open Atmospheric Science Journal* 5: 74–86.

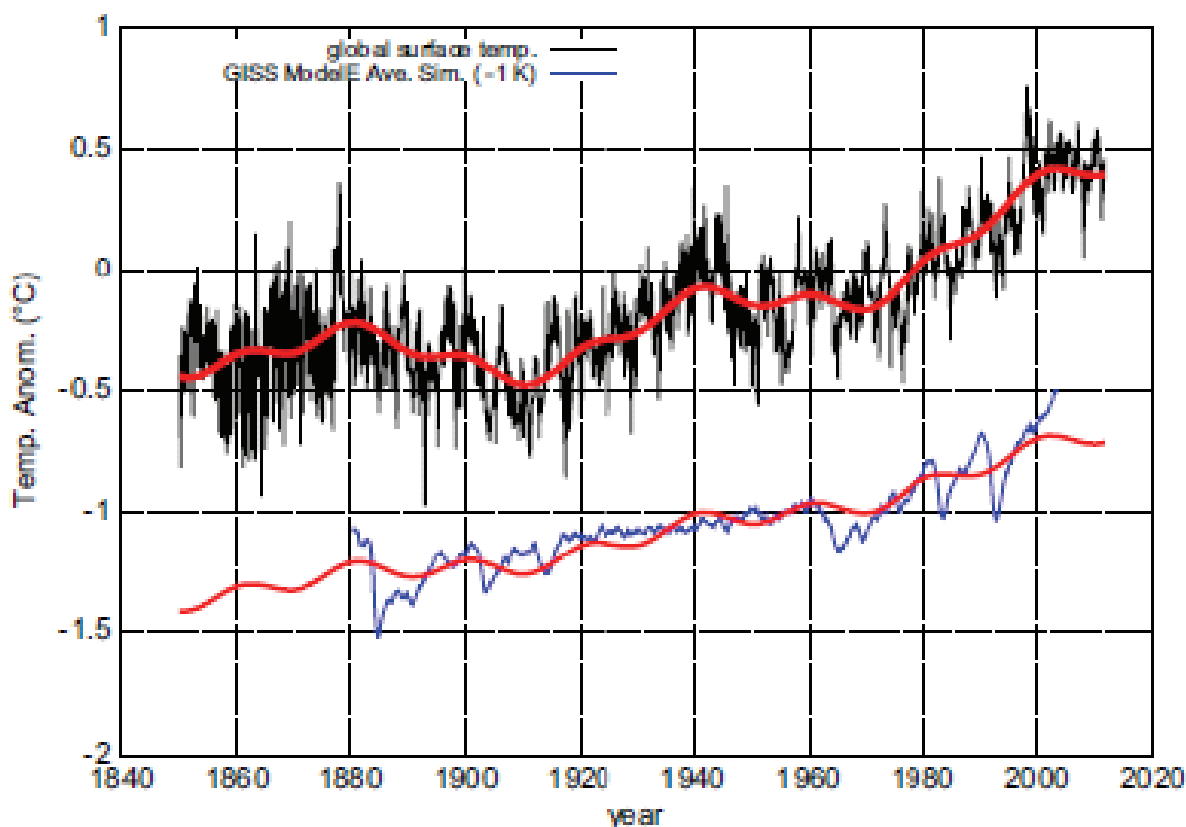


Figure 1.2.3.2.2. The global surface temperature taken from <http://www.cru.uea.ac.uk/cru/data/temperature/> (black) and the GISS ModelE average simulation (blue), and a fit using an empirical harmonic model (red). Reprinted with permission from Scafetta, N. 2011. Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation models. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 124–137, Figure 1.

Scafetta, N. 2011. Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation models. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 124–137.

1.2.4 Low Order Models

In meteorology it is well-known that the limit of dynamic predictability is approximately 10 to 14 days. This constraint is imposed by the composition of our atmosphere and the size of the planet. However, there has been some disagreement in the climate community over whether there is a fair amount of predictability in climate or whether it is too chaotic for meaningful prediction. It is appropriate here to revisit a classic work written by E.N. Lorenz nearly 50 years ago on the subject of predictability in atmospheric flows.

At the time, meteorology was interested in explaining why the mid-latitude flow (jet stream) would transition from a higher amplitude state to a

more zonal state in an irregular fashion at a time scale of roughly 10 to 14 days. There was also some interest in being able to make monthly and seasonal forecasts, which during the late 1950s to 1960s were considered very long range. During this time, numerical weather prediction was also in its infancy.

Lorenz (1963) was expressly interested in examining the behavior of periodic and non-periodic flows. Later Lorenz would describe the non-periodic behavior as “chaos,” which he then termed “*order without periodicity*.”

He used a technique called low order modeling to study the behavior of convection in a geophysical fluid. To do so he coupled the Equation of Motion and the First Law of Thermodynamics and then represented the motion and temperature variables in terms of waves, which were then characterized by the lowest wave numbers that reasonably represented these fields. He was able to demonstrate the solutions for the system in mathematical space and thus follow

the evolution of the system in time. The resultant graph is commonly known today as Lorenz's butterfly (Figure 1.2.4.1). He realized this model provided a good analogue for the behavior of mid-latitude flow.

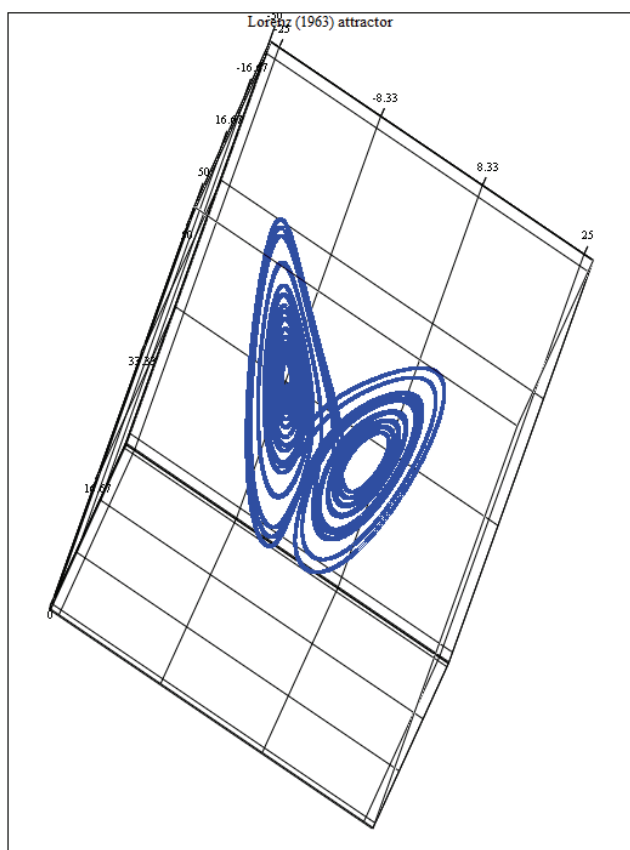


Figure 1.2.4.1. A representation of Lorenz's butterfly developed using the model published in Lorenz (1963). This figure was created in the Weather Analysis and Visualization (WAV) Lab at the University of Missouri.

In theory, then, if we know the precise initial conditions of the system such that we lay on one of the trajectories in the "butterfly," we could follow that trajectory forever and know what the state of the weather would be into the future infinitely. Computers could then make weather or climate forecasts, and meteorologists would be out of jobs.

However, even today's best models are comprised only of hypotheses about how scientists believe the atmosphere really works. As the past has made abundantly clear, state-of-the-art models of "today" quickly outlive their usefulness and are eventually replaced by the newer and improved models of "tomorrow." Today's best representation of

the physics is inadequate and there are also numerical model errors, in that differential quantities can only be estimated.

But the crux of predictability rests in the fact that the initial conditions are not precisely known. There is always a degree of uncertainty within them, and thus it is not known on which trajectory the model rests. According to Lorenz, "when our results concerning the instability of non-periodic flow are applied to the atmosphere, which is ostensibly nonperiodic, they indicate that prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long-range forecasting would seem to be non-existent." The problem of not being able to specify the precise initial state—sensitive dependence on initial conditions (SDIC)—is an integral characteristic of chaotic systems.

Lorenz's statement makes it plain that beyond 10 to 14 days, the typical timescale for the evolution of the mid-latitude flow, dynamic predictability is impossible. This is true in spite of the fact we can specify the equations representing motions in the flow. Such limits on predictability are thus scale-dependent. For example, because of their small spatial scales, we cannot dynamically predict the occurrence of individual thunderstorms beyond the 30- to 120-minute time-scale it takes for them to evolve. Beyond the time limits, corresponding to the appropriate space-scale, only statistical prediction is useful.

One way modelers attempt to mitigate SDIC is via the use of ensemble modeling. The technique is to take the initial conditions and several plausible alternative initial conditions (but very close by to the original) and run the model several times using each set. If the trajectories all evolve toward a common trajectory, the modelers claim there is high confidence that the predicted solution is highly probable. But when these trajectories diverge (another characteristic of chaotic systems), the probability that any one of them will be the actual prediction is small. Model runs of climate change scenarios exhibit this latter behavior. In these projections, the spread in the forecasts gets larger and larger as the projection time horizon lengthens. This is exactly the behavior expected from models attempting to simulate nonlinear flow—the energy of eddies below the grid scale appears chaotically as eddies on scales of the motion resolved by the grid.

Thus there is ample evidence the climate behaves

in a chaotic way and climate prediction is simply not possible; only the development of *scenarios* is possible. Although these scenarios might be statistically similar to the real climate (as opposed to accurate in detail), this observation remains to be demonstrated and cannot be assumed.

Reference

Lorenz, E.N. 1963. Deterministic nonperiodic flow. *Journal of Climate* **20**: 130–139.

1.2.5 Bias Correction

In a *Hydrology and Earth System Sciences* opinion article, Ehret *et al.* (2012) write, “despite considerable progress in recent years, output of both global and regional circulation models is still afflicted with biases to a degree that precludes its direct use, especially in climate change impact studies,” noting “this is well known, and to overcome this problem, bias correction (BC, i.e., the correction of model output towards observations in a post-processing step) has now become a standard procedure in climate change impact studies.” For example, GCMs often produce a global climate that is too cool or too warm by several degrees compared to the real world.

Ehret *et al.* present “a brief overview of state-of-the-art bias correction methods, discuss the related assumptions and implications, draw conclusions on the validity of bias correction and propose ways to cope with biased output of circulation models.”

In discussing the findings of their review, the authors state: (1) “BC methods often impair the advantages of circulation models by altering spatiotemporal field consistency, relations among variables and by violating conservation principles,” (2) “currently used BC methods largely neglect feedback mechanisms, (3) “it is unclear whether they are time-invariant under climate change conditions,” (4) “applying BC increases agreement of climate model output with observations in hindcasts and hence narrows the uncertainty range of simulations and predictions,” but (5) this is often done “without providing a satisfactory physical justification,” and this sleight of hand “is in most cases not transparent to the end user.” For example, the temperatures produced by GCMs are presented as anomalies in the IPCC reports so their disagreement with each other and with the real world are hidden.

Ehret *et al.* argue this set of negative consequences of bias correction “hides rather than

reduces uncertainty,” which they suggest may lead to avoidable forejudging of end users and decision makers. They conclude BC is often “not a valid procedure.”

Reference

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J. 2012. Should we apply bias correction to global and regional climate model data? *Hydrology and Earth System Sciences* **16**: 3391–3404.

1.3 Elements of Climate

GCMs must incorporate all the many physical, chemical, and biological processes that influence climate over different spatial and temporal scales. Although the models have evolved much in recent years, limitations and deficiencies remain.

Many important processes are either missing or inadequately represented in today’s state-of-the-art climate models. Here we highlight many of the insufficiencies researchers have found when comparing model projections against real-world observations, frequently using the researchers’ own words to report them. The list is long and varied, and it demonstrates much work remains to be done before the model simulations can be treated with the level of confidence ascribed to them by the IPCC.

1.3.1 Radiation

One of the most challenging and important problems facing today’s general circulation models of the atmosphere is how to accurately simulate the physics of Earth’s radiative energy balance. In commenting on this task, Harries (2000) stated more than a decade ago, “progress is excellent, on-going research is fascinating, but we have still a great deal to understand about the physics of climate.” He added, “we must exercise great caution over the true depth of our understanding, and our ability to forecast future climate trends.” As an example, he points out our knowledge of high cirrus clouds is very poor (it remains so today), noting “we could easily have uncertainties of many tens of W m^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing.”

Potential errors of this magnitude are extremely disconcerting in light of the fact that the radiative effect of a doubling of the air’s CO_2 content is in the lower single-digit range of W m^{-2} , and, to quote Harries, “uncertainties as large as, or larger than, the

doubled CO₂ forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes.”

Furthermore, because of the vast complexity of the subject, Harries declares, “even if [our] understanding were perfect, our ability to describe the system sufficiently well in even the largest computer models is a problem.”

Illustrative of a related problem is the work of Zender (1999), who characterized the spectral, vertical, regional, and seasonal atmospheric heating caused by the oxygen collision pairs O₂ + O₂ and O₂ + N₂, which had earlier been discovered to absorb a small but significant fraction of the globally incident solar radiation. This work revealed these molecular collisions lead to the absorption of about 1 Wm⁻² of solar radiation, globally and annually averaged. This discovery, in Zender’s words, “alters the long-standing view that H₂O, O₃, O₂, CO₂ and NO₂ are the only significant gaseous solar absorbers in Earth’s atmosphere,” and he suggests the phenomenon “should therefore be included in ... large-scale atmospheric models used to simulate climate and climate change.” Zender’s work also raises the possibility there are still other yet-to-be-discovered processes that should be included in the models used to simulate Earth’s climate, and until we are confident there is little likelihood of further such surprises, we ought not rely too heavily on what the models of today are telling us about the climate of tomorrow.

In another revealing study, Wild (1999) compared the observed amount of solar radiation absorbed in the atmosphere over equatorial Africa with what was predicted by three general circulation models of the atmosphere. Wild found the model predictions were much too small. Regional and seasonal model underestimation biases were as high as 30 Wm⁻², primarily because the models failed to properly account for spatial and temporal variations in atmospheric aerosol concentrations. In addition, Wild found the models likely underestimated the amount of solar radiation absorbed by water vapor and clouds.

Similar large model underestimations were discovered by Wild and Ohmura (1999), who analyzed a comprehensive observational data set consisting of solar radiation fluxes measured at 720 sites across Earth’s surface and corresponding top-of-the-atmosphere locations to assess the true amount of solar radiation absorbed within the atmosphere. These results were compared with estimates of solar radiation absorption derived from four atmospheric GCMs. They found “GCM atmospheres are generally

too transparent for solar radiation,” as they produce a rather substantial mean error close to 20 percent below actual observations.

Another solar-related deficiency of state-of-the-art GCMs is their failure to properly account for solar-driven variations in Earth-atmosphere processes that operate over a range of timescales extending from the 11-year solar cycle to century- and millennial-scale cycles. Although the absolute solar flux variations associated with these phenomena are small, there are a number of “multiplier effects” that may significantly amplify their impacts.

According to Chambers *et al.* (1999), most of the many nonlinear responses to solar activity variability are inadequately represented in the global climate models used by the IPCC to predict future greenhouse gas-induced global warming. Other amplifier effects are used to model past glacial/interglacial cycles and even the hypothesized CO₂-induced warming of the future, where CO₂ is not the major cause of the predicted temperature increase but rather an initial perturber of the climate system that according to the IPCC sets other, more-powerful forces in motion that produce the bulk of the ultimate warming. So there appears to be a double standard within the climate modeling community that may best be described as an inherent reluctance to deal evenhandedly with different aspects of climate change. When multiplier effects suit their purposes, they use them; but when they don’t suit their purposes, they don’t use them.

In setting the stage for their study of climate model inadequacies related to radiative forcing, Ghan *et al.* (2001) state, “present-day radiative forcing by anthropogenic greenhouse gases is estimated to be 2.1 to 2.8 Wm⁻²; the direct forcing by anthropogenic aerosols is estimated to be -0.3 to -1.5 Wm⁻², while the indirect forcing by anthropogenic aerosols is estimated to be 0 to -1.5 Wm⁻²,” so that “estimates of the total global mean present-day anthropogenic forcing range from 3 Wm⁻² to -1 Wm⁻².” This implies a climate change somewhere between a modest warming and a slight cooling. They write, “the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies.”

Pursuit of this goal, as Ghan *et al.* describe it, requires achieving “profound reductions in the uncertainties of direct and indirect forcing by anthropogenic aerosols,” which is what they set out to do. This consisted of “a combination of process

studies designed to improve understanding of the key processes involved in the forcing, closure experiments designed to evaluate that understanding, and integrated models that treat all of the necessary processes together and estimate the forcing.” At the conclusion of this laborious set of operations, Ghan *et al.* arrived at numbers that considerably reduced the range of uncertainty in the “total global mean present-day anthropogenic forcing,” but still implied a set of climate changes stretching from a small cooling to a modest warming. Thus they provided a long list of other things that must be done in order to obtain a more definitive result, after which they acknowledged even this list “is hardly complete.” They conclude their analysis by stating, “one could easily add the usual list of uncertainties in the representation of clouds, etc.” Consequently, they write, “much remains to be done before the estimates are reliable enough to base energy policy decisions upon.”

Vogelmann *et al.* (2003) also studied the aerosol-induced radiative forcing of climate, reporting, “mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux between 7 and 25 Wm^{-2} (Sokolik *et al.*, 1998),” but “only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing.” In an attempt to persuade climate modelers to rectify the situation, Vogelmann *et al.* used high-resolution spectra to calculate the surface IR radiative forcing created by aerosols encountered in the outflow of air from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. They determined “daytime surface IR forcings are often a few Wm^{-2} and can reach almost 10 Wm^{-2} for large aerosol loadings,” and these values “are comparable to or larger than the 1 to 2 Wm^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times.” The researchers conclude their results “highlight the importance of aerosol IR forcing which should be included in climate model simulations.”

Two papers published a year earlier (Chen *et al.*, 2002; Wielicki *et al.*, 2002) revealed what Hartmann (2002) called a pair of “tropical surprises.” The first of the seminal discoveries was the common finding of both groups of researchers that the amount of thermal radiation emitted to space at the top of the tropical

atmosphere increased by about 4 Wm^{-2} between the 1980s and the 1990s. The second was that the amount of reflected sunlight decreased by 1 to 2 Wm^{-2} over the same period, with the net result that more total radiant energy exited the tropics in the latter decade. In addition, the measured thermal radiative energy loss at the top of the tropical atmosphere was of the same magnitude as the thermal radiative energy gain generally predicted to result from an instantaneous doubling of the air’s CO_2 content. Yet as Hartmann noted, “only very small changes in average tropical surface temperature were observed during this time.”

The change in solar radiation reception was driven by changes in cloud cover, which allowed more solar radiation to reach the surface of Earth’s tropical region and warm it. These changes were produced by what Chen *et al.* determined to be “a decadal-time-scale strengthening of the tropical Hadley and Walker circulations.” Another factor was likely the past quarter-century’s slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean (McPhaden and Zhang, 2002); this circulation slowdown also promotes tropical sea surface warming by reducing the rate of supply of relatively colder water to the region of equatorial upwelling.

What do these observations have to do with evaluating climate models? They provide several new phenomena for the models to replicate as a test of their ability to properly represent the real world. McPhaden and Zhang note the time-varying meridional overturning circulation of the upper Pacific Ocean provides “an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific.”

In an eye-opening application of this principle, Wielicki *et al.* tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. No significant decadal variability was exhibited by any of the models and all failed to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test thus conclude “the missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved.”

Hartmann is considerably more candid in his scoring of the test, stating the results indicate “the models are deficient.” Expanding on that assessment,

he further notes, “if the energy budget can vary substantially in the absence of obvious forcing,” as it did over the past two decades, “then the climate of Earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models.”

Also concentrating on the tropics, Bellon *et al.* (2003) note “observed tropical sea-surface temperatures (SSTs) exhibit a maximum around 30°C” and “this maximum appears to be robust on various timescales, from intraseasonal to millennial.” They state, “identifying the stabilizing feedback(s) that help(s) maintain this threshold is essential in order to understand how the tropical climate reacts to an external perturbation,” which knowledge is needed for understanding how the global climate reacts to perturbations such as those produced by solar variability and the ongoing rise in atmospheric CO₂ levels. Pierrehumbert’s (1995) work confirms the importance of this matter, clearly demonstrating, in the words of Bellon *et al.*, “that the tropical climate is not determined locally, but globally.” They also note Pierrehumbert’s work demonstrates interactions between moist and dry regions are an essential part of tropical climate stability, harking back to the *adaptive infrared iris* concept of Lindzen *et al.* (2001).

Noting previous box models of tropical climate have shown it to be sensitive to the relative areas of moist and dry regions of the tropics, Bellon *et al.* analyzed various feedbacks associated with this sensitivity in a four-box model of the tropical climate “to show how they modulate the response of the tropical temperature to a radiative perturbation.” In addition, they investigated the influence of the model’s surface-wind parameterization in an attempt to shed further light on the nature of the underlying feedbacks that help define the global climate system responsible for the tropical climate observations of constrained maximum SSTs.

Bellon *et al.*’s work, as they describe it, “suggests the presence of an important and as-yet-unexplored feedback in earth’s tropical climate, that could contribute to maintain the ‘lid’ on tropical SSTs,” much like the *adaptive infrared iris* concept of Lindzen *et al.* They also say the demonstrated “dependence of the surface wind on the large-scale circulation has an important effect on the sensitivity of the tropical system,” specifically stating “this dependence reduces significantly the SST sensitivity to radiative perturbations by enhancing the evaporation feedback,” which injects more heat into the atmosphere and allows the atmospheric

circulation to export more energy to the subtropical free troposphere, where it can be radiated to space.

Clearly, therefore, the case is not closed on either the source or the significance of the maximum “allowable” SSTs of tropical regions; hence, neither is the case closed on the degree to which the planet may warm in response to continued increases in the atmospheric concentrations of carbon dioxide and other greenhouse gases.

Eisenman *et al.* (2007) reported another problem with model treatment of radiation. They used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different GCMs evaluated for the IPCC’s *Fourth Assessment Report*. Based on their analysis, they report there was a 40 Wm⁻² spread among the 16 models in terms of their calculated downward longwave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from one to more than ten meters. They note the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were “forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes?”

Answering their own question, the three researchers state “a frequently used approach” to resolving this problem “is to tune the parameters associated with the ice surface albedo” to get a more realistic answer. “In other words,” they continue, “errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components.” The three researchers conclude “the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields,” and, therefore, “the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice.”

Andronova *et al.* (2009) “used satellite-based broadband radiation observations to construct a long-term continuous 1985–2005 record of the radiative budget components at the top of the atmosphere (TOA) for the tropical region (20°S–20°N).” They then “derived the most conservative estimate of their trends” and “compared the interannual variability of the net radiative fluxes at the top of the tropical

atmosphere with model simulations from the Intergovernmental Panel on Climate Change *Fourth Assessment Report* (AR4) archive available up to 2000.” The three researchers report “the tropical system became both less reflective and more absorbing at the TOA,” and “combined with a reduction in total cloudiness (Norris, 2007), this would mean that the tropical atmosphere had recently become more transparent to incoming solar radiation, which would allow more shortwave energy to reach Earth’s surface.” They also found “none of the models simulates the overall ‘net radiative heating’ signature of the Earth’s radiative budget over the time period from 1985–2000.”

With respect to the first of their findings, and the associated finding of Norris (2007), Andronova *et al.* state these observations “are consistent with the observed near-surface temperature increase in recent years,” which provides an independent validation of the TOA radiation measurements. With respect to their second finding, the failure of all of the AR4 climate models to adequately simulate the TOA radiation measurements discredits the models. The combination of these two conclusions suggests the historical rise in the air’s CO₂ content likely has played a much lesser role in the post-Little Ice Age warming of the world than the IPCC has admitted.

In another paper, Svensson and Karlsson (2012) use several GCMs of various horizontal and vertical resolutions to examine the climate of the Arctic defined as the region north of the Arctic Circle (66.6° N). They were concerned with modelling the winter months during the period 1980–1999, a time of limited observational data sets. The observations used were the European Centre for Long Range Forecasting (ECMWF) ERA reanalyses. The authors write, “one should be cautious to interpret the data as ‘truth’ in this remote region. However, the abundance of observations at lower latitudes [in the Arctic] and sea ice extent should at least constrain the properties of the air masses that enter and exit the Arctic.” The observational data in this region were augmented with satellite observations.

Svensson and Karlsson found the winter sea ice cover was similar among the models and accorded with observations across much of the Arctic Ocean. However, there were some differences at the margins, and in the North Atlantic the overall result is that most of the models produce too much sea ice. In validating other quantities, it was found the models tend to underestimate the longwave energy being radiated into space, some by as much as 10 percent.

In terms of wintertime mean cloudiness, the models generate winter season values between 35 and 95 percent, whereas observations show values ranging from 68 percent to 82 percent, a smaller range. Near the surface, the latent and sensible heat fluxes within the Arctic were consistent with observations.

The vertical profiles (Figure 1.3.1.1) show the models were generally cooler in the lower troposphere and a little more humid. This led to wide differences between models in the characteristics of air masses. Also, all models showed stronger gradients in temperature and humidity than were observed in the lower troposphere, which resulted in lower clear-sky modelled radiation than for observations. One possible explanation was that many of the models were less “active” in terms of synoptic weather patterns in this region. From these findings, the authors infer humidity was the most important contributor to the radiation budgets in the Arctic region. This leads to the conclusion that it is important to know the models are simulating temperature and moisture profiles correctly in this region of the world.

Regional Climate Models (RCMs) are often used to simulate the climate of more limited spatial regions, especially if the focus is on phenomena driven by smaller-scale processes or even microphysical processes. Regional climate models are similar to regional forecast models in much the same way that their general circulation (GCM) counterparts are similar to global forecast models. RCMs suffer from the same deficiencies as all models, including insufficient data and resolution, model physics, and the numerical methods used.

A study by Zubler *et al.* (2011) attempted to demonstrate changes in aerosol emissions over Europe lead to changes in the radiation budgets over the region using the COSMO-CLM model (Doms and Schättler, 2002) RCM. The horizontal and vertical resolution in the RCM was finer than that in a GCM. The RCM was coupled with the aerosol model used by the European Centre for Medium Range Forecasting, Hamburg GCM and included both natural and anthropogenic aerosols. The authors performed two computer runs, one with climatologically averaged aerosols and the other with aerosol emissions that change with time (transient). On the boundaries, the RCM was driven by the European Centre re-analyses (ERA-40).

Zubler *et al.* found under clear sky conditions there was a dimming over Europe due to transient emissions from the late 1950s to the late 1970s, then a

Global Climate Models and Their Limitations

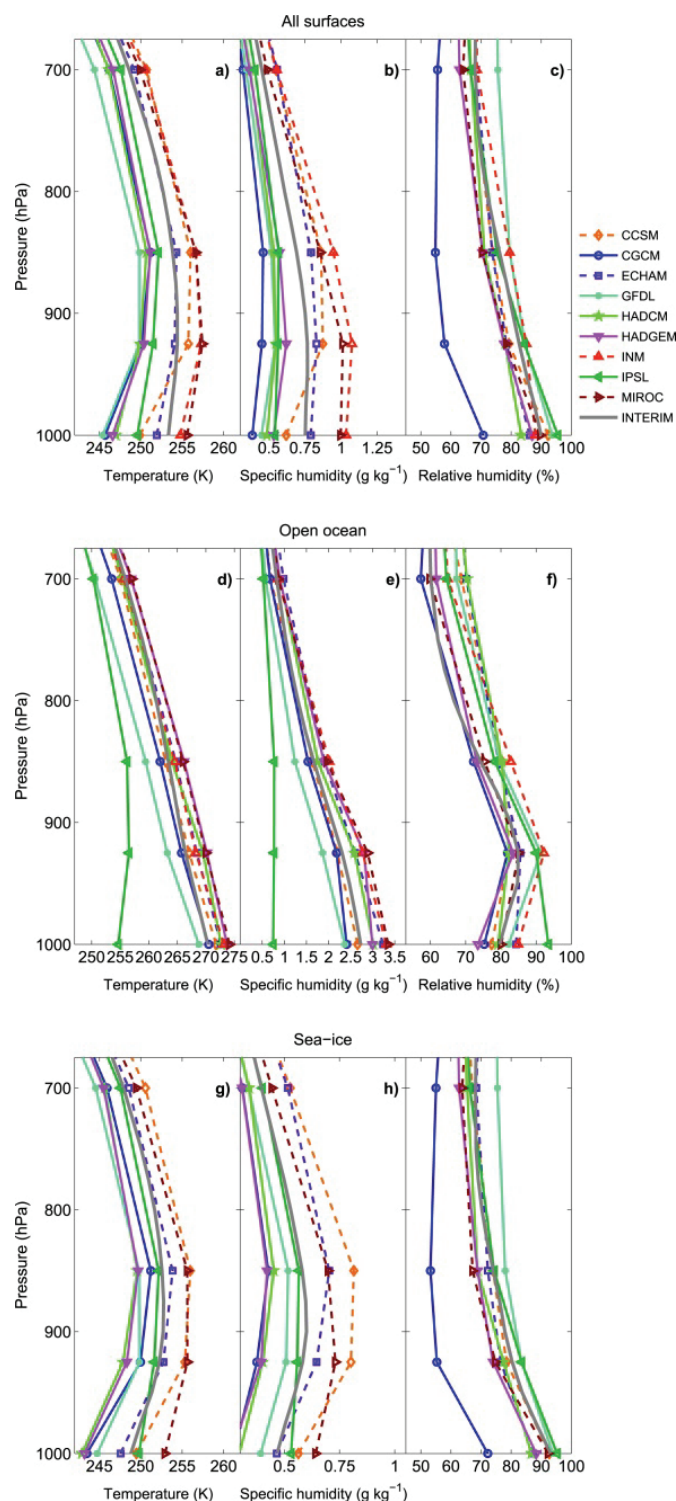


Figure 1.3.1.1. The median vertical profiles for temperature (K), specific humidity (g kg^{-1}), and relative humidity over (a)–(c) entire Arctic, (d)–(f) open ocean, and (g)–(i) sea ice from the GCMs and ERA-Interim over the southernmost latitude band 66.6° – 70°N . Reprinted with permission from Svensson, G. and J. Karlsson, 2012: On the arctic wintertime climate in global climate models. *Journal of Climate* **24**: 5757–5771. DOI:10, Figure 8.

brightening over several locales. In comparison with the ERA-40 re-analyses, they infer the RCM has underestimated the real trends. The authors also conclude processes occurring beyond the model domain were responsible for these changes, as inferred by the difference between the transient and climatological runs.

Zubler *et al.* also note the cloud fraction increased during the latter part of the twentieth century, but did so more strongly in the RCM. This would impact the total sky brightening by countering the clear sky aerosol increases. However, a strong correlation between all sky changes and the North Atlantic Oscillation (NAO) also was shown. The NAO would reflect the configuration of the storm track. Lastly, the authors found (Figure 1.3.1.2) “the use of transient emissions in TRANS does not improve the temperature trends simulated with CLIM. In line with the change in cloud fraction and thus all-sky SSR (surface shortwave radiation), both RCM simulations show a similar dimming/brightening signal in temperature.” This points to the dominance of natural variations in driving the surface temperature changes within the European Region. And as stated above, the RCM still over- and underestimated certain quantities. But as the authors note, some processes may not be so important that their actual representation is critical: “due to the dominating dependence of all-sky SSR on clouds, our study implies that it may not be necessary to use transient emissions in order to simulate dimming/brightening in Europe with a RCM.

The studies reviewed here suggest general circulation models of the atmosphere are seriously inadequate in the way they treat several aspects of Earth’s radiative energy balance—and fail entirely to address some pertinent phenomena.

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Climate Change Reconsidered II

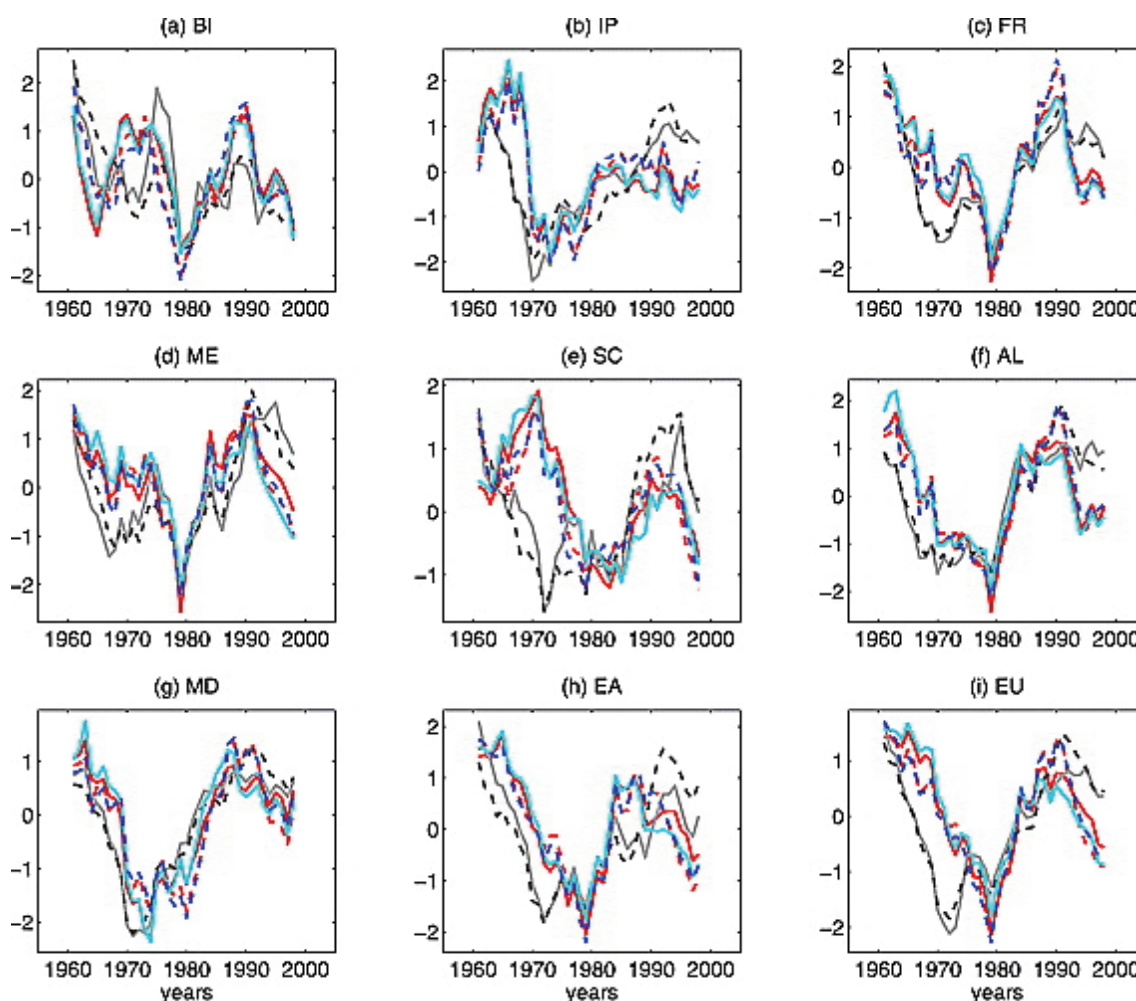


Figure 1.3.1.2. The standardized anomalies for five year running averages for various regions in Europe (see paper) for the all-sky downward surface shortwave radiation (solid black), cloud fraction multiplied by -1 (dashed black), ERA-40 (gray), transient aerosols (red), and climatological aerosols (blue). Reprinted with permission from Zubler, E.M, Folini, D., Lohmann, U., Lüthi, D., Schär, C., and M. Wild, 2011: Simulation of dimming and brightening in Europe from 1958 to 2001 using a regional climate model. *Journal of Geophysical Research* **116**: D18205, doi:10.1029/2010JD015396, Figure 5.

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1.3.2 Water Vapor

“Water vapor feedback in climate models is large and positive,” note Paltridge *et al.* (2009), and “the various model representations and parameterizations of convection, turbulent transfer, and deposition of latent heat generally maintain a more-or-less constant relative humidity (i.e., an increasing specific humidity q) at all levels in the troposphere as the planet warms.” This “increasing q amplifies the response of surface temperature to increasing CO₂ by a factor of 2 or more,” they write. They also note the behavior of water vapor in the middle and upper levels of the troposphere dominates overall water-vapor feedback. It is at these levels where long-term measurements of the trends in water vapor concentration are least reliable.

Consequently, knowledge of how q (particularly the q of the upper levels of the troposphere) responds to atmospheric warming is of paramount importance to the task of correctly predicting the water vapor feedback and how air temperatures respond to increasing CO₂ concentrations. Paltridge *et al.* explore this important subject by determining trends in relative and specific humidity at various levels in the atmosphere based on reanalysis data of the National Centers for Environmental Prediction (NCEP) for the period 1973–2007. The three researchers report “the face-value 35-year trend in zonal-average annual-average specific humidity q is significantly negative at all altitudes above 850 hPa (roughly the top of the convective boundary layer) in the tropics and southern midlatitudes and at altitudes above 600 hPa in the northern midlatitudes.” They conclude “negative trends in q as found in the NCEP data would imply that long-term water vapor feedback is negative—that it would reduce rather than amplify the response of the climate system to external forcing such as that from increasing atmospheric CO₂.”

As discussed by Boehmer (2012), there is a continuing argument on this topic that boils down to two main issues. First, there is the question as to whether *in situ* balloon measurements, which suggest a negative long-term trend in upper-level q and hence a negative water vapor feedback, or remote sensing satellite measurements, which suggest the opposite, are correct in their measurements of q . The second question concerns whether short-term correlations between upper-level q and surface temperature can be extrapolated to deduce the existence of such a correlation over longer time scales.

Boehmer’s work is critical, as the assumption that humidity will remain constant and act as an amplifier

is based largely on models, which is circular reasoning. If water vapor is not an amplifier but acts as a negative feedback, the case for high climate sensitivity and alarming rates of warming is based entirely on models and not real-world data.

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1.3.3 Aerosols

1.3.3.1 Aerosols

Aerosols, whether natural or anthropogenic, can affect the weather and climate in many ways. The most obvious is by increasing the planetary albedo, which leads to a surface cooling. Aerosols also can warm the middle and upper troposphere if they absorb sunlight, possibly increasing atmospheric stability and inhibiting cloud formation. They can have indirect effects as well, by changing the nature of clouds and the formation of precipitation. And like clouds, they can only be parameterized in weather and climate models. The inadequate treatment of aerosols by GCMs represents a major limitation in the models' reliability.

Mishchenko *et al.* (2009) state “because of the global nature of aerosol climate forcings, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change,” and they note “there have been parallel claims of unprecedented accuracy of aerosol retrievals with the moderate-resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR).”

If both aerosol retrieval systems are as good as they have been claimed to be, they should agree on a pixel by pixel basis as well as globally. Consequently, and noting “both instruments have been flown for many years on the same Terra platform, which provides a unique opportunity to compare fully collocated pixel-level MODIS and MISR aerosol retrievals directly,” Mishchenko *et al.* decided to see how they compare in this regard by analyzing eight years of such data.

The six scientists from NASA's Goddard Institute for Space Studies report finding what they describe as “unexpected significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties.” In fact, they note, “the only point on which both datasets seem to fully agree is that there may have been a weak increasing tendency in the globally averaged aerosol optical thickness (AOT) over the land and no long-term AOT tendency over the oceans.” The NASA scientists state their conclusion quite succinctly: “[O]ur new results suggest that the current knowledge of the global distribution of the AOT and, especially, aerosol microphysical characteristics remains unsatisfactory.” And since this knowledge is indispensable “for use in various assessments of climate and climate change,” it would appear current assessments of greenhouse-gas forcing of climate made by the best models in use today may be of very little worth in describing the real world of nature.

In a contemporaneous study, Haerter *et al.* (2009) note future projections of climate “have been—for a given climate model—derived using a ‘standard’ set of cloud parameters that produce realistic present-day climate.” However, they add, “there may exist another set of parameters that produces a similar present-day climate but is more appropriate for the description of climate change” and, “due to the high sensitivity of aerosol forcing (F) to cloud parameters, the climate projection with this set of parameters could be notably different from that obtained from the standard set of parameters, even though the present-day climate is reproduced adequately.” This state of affairs suggests replication of the present-day climate is no assurance that a climate model will accurately portray Earth's climate at some future time. It is also noted this study did not examine first principles, but rather the treatment of radiational forcing, which must be parameterized.

To get a better idea of the magnitude of uncertainty associated with this conundrum, Haerter *et al.* used the ECHAM5 atmospheric general circulation model, which includes parameterizations of direct and first indirect aerosol effects, to determine what degree of variability in F results from reasonable uncertainties associated with seven different cloud parameters: the entrainment rate (the rate at which environmental air and cloud air mix) for shallow convection, the entrainment rate for penetrative convection, the cloud mass flux above the non-buoyancy level, the correction to asymmetry parameter for ice clouds, the inhomogeneity

parameter for liquid clouds, the inhomogeneity parameter for ice clouds, and the conversion efficiency from cloud water to precipitation.

Upon completion of their analyses, the four researchers report “the uncertainty due to a single one of these parameters can be as large as 0.5 W/m^2 ” and “the uncertainty due to combinations of these parameters can reach more than 1 W/m^2 .” As for the significance of their findings, they write, “these numbers should be compared with the sulfate aerosol forcing of -1.9 W/m^2 for the year 2000, obtained using the default values of the parameters.”

The mean sulfate aerosol forcing component of Earth’s top-of-the-atmosphere radiative budget is thus apparently not known to within anything better than ± 50 percent. In addition, Haerter *et al.* (2009) note structural uncertainties, such as “uncertainties in aerosol sources, representation of aerosols in models, parameterizations that relate aerosols and cloud droplets to simulate the indirect aerosol effect, and in cloud schemes” lead to an overall uncertainty in F of approximately ± 43 percent, as noted by IPCC. In reality, therefore, the current atmosphere’s aerosol radiative forcing is probably not known to anything better than $\pm 100\%$, which does not engender confidence in the ability to simulate Earth’s climate very far into the future.

In another study, Booth *et al.* (2012) note “a number of studies have provided evidence that aerosols can influence long-term changes in sea surface temperatures,” citing Mann and Emanuel (2006) and Evan *et al.* (2009), but “climate models have so far failed to reproduce these interactions,” citing Knight (2009) and Ting *et al.* (2009). They consequently note, as they phrase it, “the role of aerosols in decadal variability remains unclear.”

Booth *et al.* used the Hadley Centre Global Environmental Model version 2 (HadGEM2-ES)—a next-generation Climate Model Intercomparison Project phase 5 (CMIP5) model—to determine whether older CMIP3 models “contained the complexity necessary to represent a forced Atlantic Multidecadal Oscillation.” The five researchers were thus able to demonstrate that “aerosol emissions and periods of volcanic activity explain 76% of the simulated multidecadal variance in detrended 1860–2005 North Atlantic sea surface temperatures,” and “after 1950, simulated variability is within observational estimates,” while their estimates for 1910–1940 “capture twice the warming of previous generation models,” although they still “do not explain the entire observed trend.” Put another way,

they state that “mechanistically, we find that inclusion of aerosol-cloud microphysical effects, which were included in few previous multimodel ensembles, dominates the magnitude (80%) and the spatial pattern of the total surface aerosol forcing in the North Atlantic.”

Booth *et al.* conclude their paper by noting, “one of the reasons why the role of aerosols in driving multidecadal variability has not previously been identified” is that “although all the CMIP3 models represented the direct effect of aerosols on shortwave radiation, most omitted or only partly represented the indirect aerosol effects,” citing Chang *et al.* (2011). They conclude, “we need to reassess the current attribution to natural ocean variability of a number of prominent past climate impacts linked to North Atlantic sea surface temperatures.”

Similarly, it may be that climatologists need to reassess the attribution of the post-Little Ice Age warming of the world to anthropogenic CO_2 emissions, to account for the possible warming effects of still other as-yet-unappreciated phenomena that are either “omitted or only partly represented” in current state-of-the-art climate models. Some of these phenomena may be associated with things transpiring on (or within) the Sun; other phenomena that may thwart or significantly reduce the warming effect of rising atmospheric CO_2 concentrations may be associated with a variety of biological responses of both marine and terrestrial vegetation to atmospheric CO_2 enrichment, as well as to warming itself.

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1.3.3.2 Aerosol Nuclei

Many physical processes must be approximated in GCMs using separate calculations at the grid scale, called parameterizations. In many cases this involves averaging the effect of subgrid scale processes. These processes include the existence and formation of clouds and also relate to the presence of aerosols or particulates in the air that are not considered to be part of the basic makeup the atmosphere but which strongly affect radiation fluxes. Aerosols are important because they can affect energy exchanges in the atmosphere and serve as condensation nuclei for cloud formation. Clouds have an impact on Earth's energy budget through their ability to reflect and scatter light and to absorb and emit infrared radiation. Also, cloud properties such as droplet size and concentration can influence how effectively clouds contribute to the planet's albedo.

Roesler and Penner (2010) used a microphysical model to explore the effects of the chemical composition and size of aerosols on the concentration of cloud droplets over the United States. Using aerosol composition measurements from 1988 to 2004, the authors found aerosols influenced the size and concentration of the cloud droplets that ultimately formed in their experiments.

They also included tests varying the strength of the atmospheric vertical motions lifting air parcels, which are initially saturated, over a distance of about 300 meters in order to induce cloud formation. They found that as vertical motion increased in strength within their model, the number of cloud droplets increased. They also found that larger aerosols, though fewer in number, were more soluble as they formed cloud droplets. Smaller aerosols were more

numerous but less soluble. Thus, the larger aerosols were found to be better at producing cloud droplets. The size of the aerosols depended on their chemical composition, which varied by region across the United States and by season. They found the concentrations of droplets were largest in the eastern U.S. and in the spring season.

Roesler and Penner's work makes clear that in order to model cloud forcing in a GCM, which ultimately affects the ability of the model to capture climate or climate change, the chemical composition of the condensation nuclei that form these clouds must be properly accounted. Roesler and Penner pointed out, "a global model using an empirical relationship based on regional measurements could over- or under-predict droplet concentrations when applied to other regions depending on differences in composition." GCMs must not ignore the chemical composition of aerosols—but they currently do.

In another study, Golaz *et al.* (2011) used the most recently released version of the Geophysical Fluid Dynamics Laboratory's (GFDL) Atmospheric General Circulation Model (AGCM), called AM3 (Donner *et al.*, 2011), to explore the "aerosol indirect effect" (AIE) using a prognostic parameterization scheme for cloud droplet numbers. The AIE is simply the impact particulates and chemicals have on Earth's radiation budget by their influence on cloud properties. Cloud properties such as composition (ice versus water), droplet size, and droplet density are critical determinants of how clouds influence Earth's radiation budget.

Past studies have shown cloud droplet numbers are a function of aerosol types, temperature, pressure, and vertical motion (which in stratiform clouds is related to turbulence). Golaz *et al.* provided a six-year control simulation of climate after allowing one year for model equilibration. Then they changed the cloud droplet numbers in a predictive cloud scheme by reducing the turbulence in the model (experiment 1). In the second experiment an additional adjustment was made by allowing droplet formation in new clouds and preexisting clouds. The third and final experiment adjusted the vertical motion profile and the turbulence used in experiment 2.

When these experiments were run for one year, the latter two experiments produced more droplets, making the clouds more reflective and resulting in less incoming solar radiation. Golaz *et al.* note the differences among all the experiments were similar to the radiative forcing differences between today and preindustrial times. But they also observe these short-

term experiments “could not be used for long-term coupled climate experiments, because the magnitude of their net top-of-the-atmosphere (TOA) radiation fluxes is unrealistically large.” The model configurations were readjusted to bring energy balance in line with the reference run.

The exact formulation of model physics and assumptions used for variables such as cloud droplet numbers can have a large impact on the predicted droplet numbers. These in turn can have a relatively large impact on the net radiation budgets. Golaz *et al.* showed that, in spite of these differences, there was only a small impact on the present-day climate overall. However, when the three formulations were applied between present-day and pre-industrial climate, there was a large difference in the net radiation budgets, which can be attributed to the AEI (Figure 1.3.3.2.1). This likely would result in the model yielding “an unrealistic temperature evolution [from preindustrial to current times] compared to observations.”

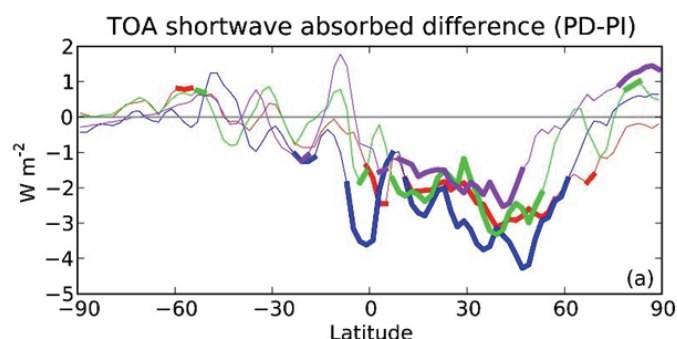


Figure 1.3.3.2.1. The zonal mean difference in the top of the atmosphere shortwave absorption between model runs with present-day conditions and preindustrial conditions using the control and three experimental parameterizations described here. The thicker lines indicate which results are statistically significant at the 95% confidence level. The red line represents the control run, and the blue, green, and purple represent the model configured for differences in cloud formation. Reprinted with permission from Golaz, J.-C., Salzmann, M., Donner, L.J., Horowitz, L.W., Ming, Y., and Zhao, M. 2011. Sensitivity of the aerosol indirect effect to subgrid variability in the cloud parameterization of the GFDL atmosphere general circulation model AM3. *Journal of Climate* **24**: 3145–3160, Figure 5a.

This paper demonstrates that uncertainty in model formulations, especially processes such as cloud parameterizations, can yield considerable uncertainty in climate projections and scenarios. The results also show the expected magnitude of the

output is not known and model physics (parameterizations) must be adjusted within allowable ranges to conform with our current understanding of a process, or back towards basic conservation laws. These precautions are what many scientists have advised when looking at future climate scenarios.

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1.3.3.3 Volcanic Aerosols

The effects of volcanic eruptions on climate have been studied and are well-known. Volcanic eruptions eject particulate and aerosol materials into the stratosphere. These aerosols, primarily sulfate type, increase the albedo of the planet, resulting in less incoming solar radiation and a cooling of the lower troposphere and surface. Generally, the greater the eruption, the stronger this effect will be and the longer it will last. Volcanic eruptions whose emissions are confined to the troposphere generally have little effect on climate, as the troposphere is more efficient in scavenging out the relatively large particulates.

Volcanism is an “external” forcing to Earth’s atmosphere and its occurrence is considered to be unpredictable and irregular. However, once the particulate matter and aerosols are injected into the atmosphere, it is possible to project the spread of the material using a GCM. In June 2009, the Sarychev

volcano in Russia's Kamchatka Peninsula erupted explosively for approximately five days. At the time it was the second such eruption within a year. It injected 1.2 teragrams (Tg) of material into the atmosphere to an estimated height of as much as 16 km—nearly 10 miles.

Kravitz *et al.* (2011) studied measurements of the optical depth of the aerosol sulfates from this eruption and compared these with the projected output from a 20-member ensemble using a GCM, with the goal of providing suggestions for improving the model's capabilities. They used the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies Model-E, which employs a coupled atmosphere-ocean GCM with fairly coarse resolution in the horizontal (4° by 5° lat/lon) and vertical (23 layers). The model contained levels up to 80 km, necessarily including the stratosphere.

The control model run consisted of a 20-member suite globally from 2007 to 2010. In the experiment, 1.5 Tg of volcanic material was injected into the atmosphere at a point near Sarychev in 2008 of the model year. The observed aerosol measurements came from ground-based LIDARS at six locations around the world as well as satellite-based measurements that profile the aerosol concentration using scattered sunlight (Optical Spectrograph and Infrared Imaging System (OSIRIS)).

The model did a reasonably good job of spreading the volcanic material around the Northern Hemisphere, but there were some important discrepancies between the model and observations (e.g. Figure 1.3.3.3.1). For example, the model transported the material too quickly into the tropics and too slowly into the high latitudes. The authors speculate this error may indicate a need to improve the model's depiction of stratospheric circulation. Also, the model tended to remove aerosols too quickly from the atmosphere, especially in the high latitudes, which may have been an indication of model overestimation of particulate size. Note that in Figure 1.3.3.3.1, the modeled peak aerosol values occurred one month earlier than observed and then decreased in concentration too quickly.

The sensitivity of GCMs to aerosol forcing also can be assessed based on volcanic activity. The Pinatubo eruption of 1991 was very large and explosive, injecting a huge amount of sulfate aerosols into the atmosphere. The climate cooled in response, but the climate models cooled much more than the actual atmosphere, showing the models assumed strong radiative forcing (cooling) by sulfate aerosols,

a result also noted by Landrum *et al.* (2013).

This is important because one of the key assumptions of the models is that human pollution, particularly in the pre-1970 period, strongly dampens out the warming that greenhouse gas emissions otherwise would have caused. For most of the period simulated, however, no data (or only fragmentary data) are available to estimate sulfate aerosol pollution. Furthermore, the forcing by any given level of aerosols is not easily measured and is usually estimated from model responses to things like volcanic activity, which is not a direct parallel to human pollution. Thus the aerosol forcing history of the twentieth century used by the IPCC is very approximate, and in fact different histories are often used by different modeling groups. Kiehl (2007) found GCMs with a larger anthropogenic forcing (more warming, which varied by a factor of 2) used a larger aerosol forcing (compensating cooling, which varied by a factor of 3). Modeling groups thus appear to have chosen an aerosol history that makes their model fit the historical record or tuned their model to accommodate the aerosol history they utilized.

Allen *et al.* (2013) found models do not capture the global dimming from the 1950s to 1980s and brightening from the 1990s, which implies “model underestimation of the observed trends is related to underestimation of aerosol radiative forcing and/or deficient aerosol emission inventories.” This undermines the claim that the models are simply deduced from basic physics, and it also explains why they currently seem to be running hotter than the actual climate.

Volcanic aerosols represent yet another demonstration that climate models have a difficult time representing the impact of external and seemingly “random” forcing processes. The likely impact on surface temperatures from the Kravitz *et al.* (2011) experiment would be a bias toward warm temperatures on the time scale of months.

Driscoll *et al.* (2012) report that Stenchikov *et al.* (2006) analyzed seven models used in the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC, 2007) that “included all the models that specifically represented volcanic eruptions.” The scientists found the strength and spatial pattern of the surface temperature anomalies predicted by them were not “well reproduced.” Hoping to find some improvement in more recent versions of the models, Driscoll *et al.* repeated the analysis of Stenchikov *et al.* (2006), using 13 model simulations from the Coupled Model Intercomparison

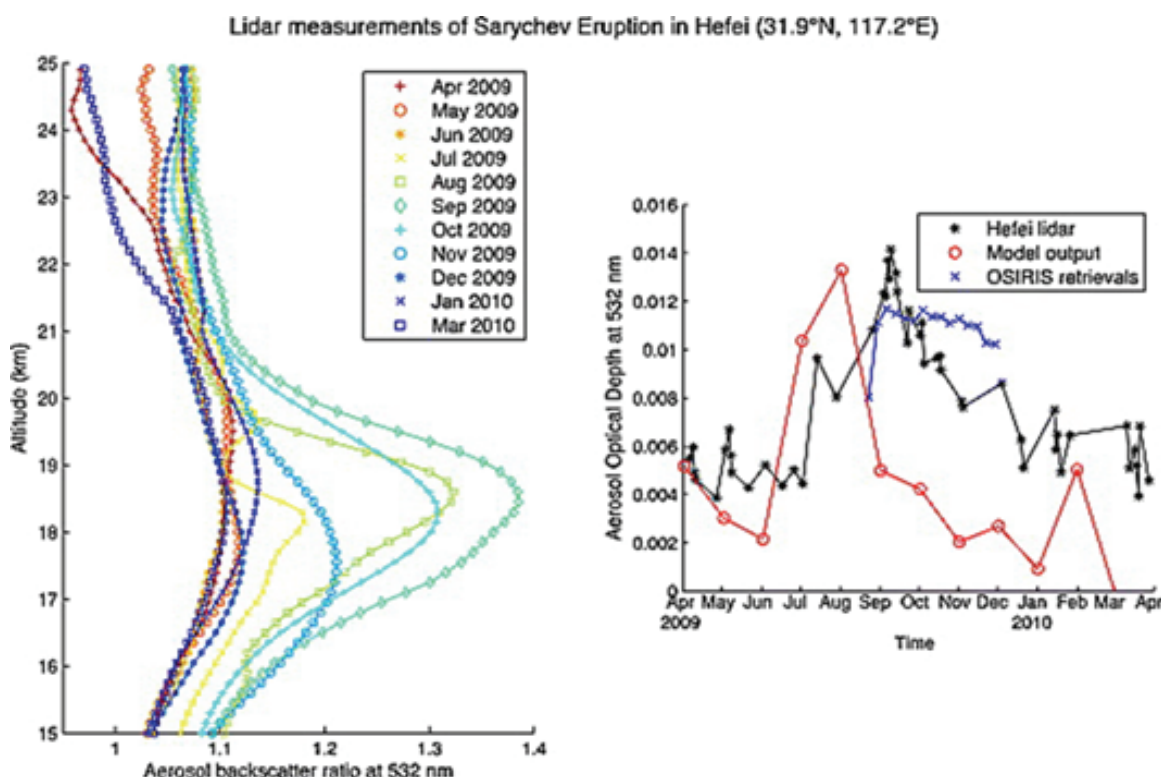


Figure 1.3.3.1. The LIDAR retrievals from Hefei, China as compared to model output and OSIRIS retrievals (left). The monthly averages of backscatter as a function of altitude maximizing in September 2009 (right). The integrated (15–25 km) optical depth through the stratosphere for the LIDAR data (black), zonally averaged stratospheric aerosol optical depth calculated by the model in the grid latitude containing the Hefei LIDAR (28°–32°N) (red), and OSIRIS retrievals zonally averaged over the latitude band 30°–35°N (blue). Reprinted with permission from Kravitz, B., Robock, A., Bourassa, A., Deshler, T., Wu, D., Mattis, I., Finger, F., Hoffmann, A., Ritter, C., Bitar, L., Duck, T.J., and Barnes J.E. 2011. Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. *Journal of Geophysical Research-Atmospheres* **116**: D18211, doi:10.1029/2010JD015501, Figure 11.

Project phase 5 (CMIP5)—an overview of which is given by Taylor *et al.* (2011)—while focusing their analysis on the regional impacts of the largest volcanic eruptions on the Northern Hemisphere (NH) large-scale circulation during the winter season.

According to the five researchers, “the models generally fail to capture the NH dynamical response following eruptions.” More specifically, they state the models “do not sufficiently simulate the observed post-volcanic strengthened NH polar vortex, positive North Atlantic Oscillation, or NH Eurasian warming pattern, and they tend to overestimate the cooling in the tropical troposphere.” They also note “none of the models simulate a sufficiently strong reduction in the geopotential height at high latitudes,” and correspondingly, “the mean sea level pressure fields and temperature fields show major differences with respect to the observed anomalies.” In addition, they find “all models show considerably less variability in

high-latitude stratospheric winds than observed,” and “none of the models tested have a Quasi-Biennial Oscillation in them.”

Given such “substantially different dynamics between the models,” Driscoll *et al.* report they had “hoped to find at least one model simulation that was dynamically consistent with observations, showing improvement since Stenchikov *et al.* (2006).” But “disappointingly,” they found “despite relatively consistent post volcanic radiative changes, none of the models manage to simulate a sufficiently strong dynamical response.” They say their study “confirms previous similar evaluations and raises concern for the ability of current climate models to simulate the response of a major mode of global circulation variability to external forcings,” noting “this is also of concern for the accuracy of geoengineering modeling studies that assess the atmospheric response to stratosphere-injected particles.”

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- succeeding. The lack of success may not be due entirely to inadequate model resolution: If cloud processes have not been adequately and properly quantified, not even the highest resolution will bring success.
- Lane *et al.* (2000) evaluated the sensitivities of the cloud-radiation parameterizations utilized in contemporary GCMs to changes in vertical model resolution, varying the latter from 16 to 60 layers in increments of four and comparing the results to observed values. This effort revealed cloud fraction varied by approximately 10 percent over the range of resolutions tested, which corresponded to about 20 percent of the observed cloud cover fraction. Similarly, outgoing longwave radiation varied by 10 to 20 Wm^{-2} as model vertical resolution was varied, amounting to approximately 5 to 10 percent of observed values, and incoming solar radiation experienced similar significant variations across the range of resolutions tested. The model results did not converge, even at a resolution of 60 layers.
- In an analysis of the multiple roles played by cloud microphysical processes in determining tropical climate, Grabowski (2000) found much the same thing, noting there were serious problems of computer models failing to correctly incorporate cloud microphysics. These observations led him to conclude “it is unlikely that traditional convection parameterizations can be used to address this fundamental question in an effective way.” He also became convinced that “classical convection parameterizations do not include realistic elements of cloud physics and they represent interactions among cloud physics, radiative processes, and surface processes within a very limited scope.” Consequently, he added, “model results must be treated as qualitative rather than quantitative.”
- Reaching similar conclusions were Gordon *et al.* (2000), who determined many GCMs of the late 1990s tended to under-predict the presence of subtropical marine stratocumulus clouds and failed to simulate the seasonal cycle of clouds. These deficiencies are important because these particular clouds exert a major cooling influence on the surface temperatures of the sea below them. In the situation investigated by Gordon and his colleagues, the removal of the low clouds, as occurred in the normal application of their model, led to sea surface temperature increases on the order of 5.5°C.
- Further condemnation of turn-of-the-century model treatments of clouds came from Harries (2000), who write our knowledge of high cirrus

clouds is very poor and “we could easily have uncertainties of many tens of Wm^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing.”

Lindzen *et al.* (2001) analyzed cloud cover and sea surface temperature (SST) data over a large portion of the Pacific Ocean, finding a strong inverse relationship between upper-level cloud area and mean SST, such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreased by about 22 percent for each degree C increase in cloudy region SST. Essentially, as the researchers describe it, “the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature.” The sensitivity of this negative feedback was calculated by Lindzen *et al.* to be substantial. They estimate it would “more than cancel all the positive feedbacks in the more sensitive current climate models” being used to predict the consequences of projected increases in atmospheric CO_2 concentration.

Lindzen’s conclusions did not go uncontested, and Hartmann and Michelsen (2002) quickly claimed the correlation noted by Lindzen *et al.* resulted from variations in subtropical clouds not physically connected to deep convection near the equator, and it was thus “unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases.” Fu *et al.* (2002) also chipped away at the adaptive infrared iris concept, arguing “the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive,” while also claiming to show water vapor and low cloud effects were overestimated by Lindzen *et al.* by at least 60 percent and 33 percent, respectively. As a result, Fu *et al.* obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al.*’s much larger negative feedback factor of -0.45 to -1.03.

In a contemporaneously published reply to this critique, Chou *et al.* (2002) state Fu *et al.*’s approach of specifying longwave emission and cloud albedos “appears to be inappropriate for studying the iris effect.” Since “thin cirrus are widespread in the tropics and ... low boundary clouds are optically thick, the cloud albedo calculated by [Fu *et al.*] is too large for cirrus clouds and too small for boundary layer clouds,” they write, so “the near-zero contrast in

cloud albedos derived by [Fu *et al.*] has the effect of underestimating the iris effect.” In the end, Chou *et al.* agreed Lindzen *et al.* “may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al.*].”

Grassl (2000), in a review of the then-current status of the climate-modeling enterprise two years before the infrared iris effect debate emerged, noted changes in many climate-related phenomena, including cloud optical and precipitation properties caused by changes in the spectrum of cloud condensation nuclei, were insufficiently well known to provide useful insights into future conditions. In light of this knowledge gap, he recommended “we must continuously evaluate and improve the GCMs we use,” although he acknowledges contemporary climate model results were already being “used by many decision-makers, including governments.”

Some may consider what is currently known about clouds to be sufficient for predictive purposes, but the host of questions posed by Grassl—for which definitive answers are still lacking—demonstrates this assumption is erroneous. As but a single example, Charlson *et al.* (1987) describe a negative feedback process that links biologically produced dimethyl sulfide (DMS) in the oceans with climate. (See Chapter 2 of this volume for a more complete discussion of this topic.) This hypothesis holds that the global radiation balance is significantly influenced by the albedo of marine stratus clouds and that the albedo of these clouds is a function of cloud droplet concentration, which is dependent upon the availability of condensation nuclei that have their origin in the flux of DMS from the world’s oceans to the atmosphere.

Acknowledging that the roles played by DMS oxidation products in the context described above are “diverse and complex” and in many instances “not well understood,” Ayers and Gillett (2000) summarized empirical evidence, derived from data collected at Cape Grim, Tasmania, and from reports of other pertinent studies in the peer-reviewed scientific literature, supporting Charlson *et al.*’s (1987) hypothesis. Ayers and Gillett found the “major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis” and there is “compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere.”

The empirical evidence analyzed by Ayers and

Gillett highlights an important suite of negative feedback processes that act in opposition to model-predicted CO₂-induced global warming over the world's oceans. These processes are not fully incorporated into even the best of the current climate models, nor are analogous phenomena that occur over land included in them, such as those discussed by Idso (1990).

Further to this point, O'Dowd *et al.* (2004) measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms at various times of the year. They found in the winter, when biological activity was at its lowest, the organic fraction of the sub-micrometer aerosol mass was about 15 percent. During the spring through autumn, however, when biological activity was high, "the organic fraction dominates and contributes 63 percent to the sub-micrometer aerosol mass (about 45 percent is water-insoluble and about 18 percent water-soluble)," they write. Based on these findings, they performed model simulations that indicated the marine-derived organic matter "can enhance the cloud droplet concentration by 15 percent to more than 100 percent and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota."

O'Dowd *et al.* (2004) state their findings "completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models," or as they note elsewhere in their paper, "an important source of organic matter from the ocean is omitted from current climate-modeling predictions and should be taken into account."

Another perspective on the cloud-climate conundrum is provided by Randall *et al.* (2003), who state at the outset of their review of the subject that "the representation of cloud processes in global atmospheric models has been recognized for decades as the source of much of the uncertainty surrounding predictions of climate variability." They report that "despite the best efforts of [the climate modeling] community ... the problem remains largely unsolved" and note, "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future."

Randall *et al.* declare "clouds are complicated," highlighting what they call the "appalling complexity" of the cloud parameterization situation. They also state "our understanding of the interactions of the hot towers [of cumulus convection] with the global circulation is still in a fairly primitive state," and not knowing all that much about what goes up, it's not surprising we also don't know much about what comes down, as they report "downdrafts are either not parameterized or crudely parameterized in large-scale models." It also should be noted Riehl and Malkus (1958), in an analysis of the equatorial trough region, could not achieve closure of their large-scale energy budgets without resorting to significant vertical exchanges by way of the cumulonimbus downdrafts.

With respect to stratiform clouds, the situation is no better, as their parameterizations are described by Randall *et al.* as "very rough caricatures of reality." As for interactions between convective and stratiform clouds, during the 1970s and '80s, Randall *et al.* report "cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds." They reported the concept of detrainment was "somewhat murky" and the conditions that trigger detrainment were "imperfectly understood." "At this time," as they put it, "no existing GCM includes a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall *et al.* additionally state "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they report only a few GCMs have even attempted to do so. Why? Because, as they continue, "the cloud parameterization problem is overwhelmingly complicated" and "cloud parameterization developers," as they call them, are still "struggling to identify the most important processes on the basis of woefully incomplete observations." They add, "there is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard." The four scientists conclude, "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

To show the basis for this conclusion is robust and cannot be said to rest on the less-than-enthusiastic remarks of a handful of exasperated climate modelers, additional studies on the subject have been published subsequent to Randall *et al.*, any of which could have readily refuted their assessment of the situation if they

thought it was appropriate.

Siebesma *et al.* (2004), for example, report “simulations with nine large-scale models [were] carried out for June/July/August 1998 and the quality of the results [was] assessed along a cross-section in the subtropical and tropical North Pacific ranging from (235°E, 35°N) to (187.5°E, 1°S),” in order to “document the performance quality of state-of-the-art GCMs in modeling the first-order characteristics of subtropical and tropical cloud systems.” The main conclusions of this study, according to the authors are: “(1) almost all models strongly under predicted both cloud cover and cloud amount in the stratocumulus regions while (2) the situation is opposite in the trade-wind region and the tropics where cloud cover and cloud amount are over predicted by most models.” They report “these deficiencies result in an over prediction of the downwelling surface short-wave radiation of typically 60 Wm⁻² in the stratocumulus regimes and a similar under prediction of 60 Wm⁻² in the trade-wind regions and in the intertropical convergence zone (ITCZ),” and these discrepancies are to be compared with a radiative forcing of only a couple of Wm⁻² for a 300 ppm increase in the atmosphere’s CO₂ concentration. In addition, they note “similar biases for the short-wave radiation were found at the top of the atmosphere, while discrepancies in the outgoing long-wave radiation are most pronounced in the ITCZ.”

The 17 scientists hailing from nine different countries who comprised Siebesma *et al.* also found “the representation of clouds in general-circulation models remains one of the most important as yet unresolved issues in atmospheric modeling.” This is partially due, they continue, “to the overwhelming variety of clouds observed in the atmosphere, but even more so due to the large number of physical processes governing cloud formation and evolution as well as the great complexity of their interactions.” Hence, they conclude that through repeated critical evaluations of the type they conducted, “the scientific community will be forced to develop further physically sound parameterizations that ultimately result in models that are capable of simulating our climate system with increasing realism.”

In their effort to assess the status of state-of-the-art climate models in simulating cloud-related processes, Zhang *et al.* (2005) compared basic cloud climatologies derived from ten atmospheric GCMs with satellite measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) and the Clouds and Earth’s Radiant Energy

System (CERES) program. ISCCP data were available for 1983–2001, and data from the CERES program were available for the winter months of 2001 and 2002 and for the summer months of 2000 and 2001. The purpose of their analysis was twofold: to assess the current status of climate models in simulating clouds so that future progress can be measured more objectively, and to reveal serious deficiencies in the models so as to improve them.

The work of 20 climate modelers involved in this exercise revealed a long list of major model imperfections. First, Zhang *et al.* report a fourfold difference in high clouds among the models, and that the majority of the models simulated only 30 to 40 percent of the observed middle clouds, with some models simulating less than a quarter of observed middle clouds. For low clouds, they report half the models underestimated them, such that the grand mean of low clouds from all models was only 70 to 80 percent of what was observed. Furthermore, when stratified in optical thickness ranges, the majority of the models simulated optically thick clouds more than twice as frequently as was found to be the case in the satellite observations, and the grand mean of all models simulated about 80 percent of optically intermediate clouds and 60 percent of optically thin clouds. In the case of individual cloud types, the group of researchers note “differences of seasonal amplitudes among the models and satellite measurements can reach several hundred percent.” Zhang *et al.* (2005) conclude “much more needs to be done to fully understand the physical causes of model cloud biases presented here and to improve the models.”

L’Ecuyer and Stephens (2007) used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period from January 1998 through December 1999 in order to evaluate the sensitivity of atmospheric heating—and the factors that modify it—to changes in east-west sea surface temperature gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere that were utilized in the IPCC’s most recent *Fourth Assessment Report*. This protocol, in their words, “provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures.”

Results indicate “a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event.” They also found “the inter-model variability in the responses of precipitation, total heating, and vertical motion is often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO.” In addition, they report “many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds.” As a result of these much-less-than-adequate findings, the two researchers from Colorado State University’s Department of Atmospheric Science conclude “deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models,” and these deficiencies “cannot be ignored when interpreting their predictions of future climate.”

In a contemporaneous publication, this one in the *Journal of the Atmospheric Sciences*, Zhou *et al.* (2007) state “clouds and precipitation play key roles in linking the Earth’s energy cycle and water cycles,” noting “the sensitivity of deep convective cloud systems and their associated precipitation efficiency in response to climate change are key factors in predicting the future climate.” They also report cloud-resolving models, or CRMs, “have become one of the primary tools to develop the physical parameterizations of moist and other subgrid-scale processes in global circulation and climate models,” and CRMs could someday be used in place of traditional cloud parameterizations in such models.

In this regard, the authors note “CRMs still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies.” To help stimulate progress in these areas, the nine scientists compared the cloud and precipitation properties observed from CERES and Tropical Rainfall Measuring Mission (TRMM) instruments against simulations obtained from the three-dimensional Goddard Cumulus Ensemble (GCE) model during the South China Sea Monsoon Experiment (SCSMEX) field campaign of 18 May–18 June 1998.

Zhou *et al.* report: (1) “the model has much higher domain-averaged OLR (outgoing longwave radiation) due to smaller total cloud fraction”; (2) “the

model has a more skewed distribution of OLR and effective cloud top than CERES observations, indicating that the model’s cloud field is insufficient in area extent”; (3) “the GCE is ... not very efficient in stratiform rain conditions because of the large amounts of slowly falling snow and graupel that are simulated”; and (4) “large differences between model and observations exist in the rain spectrum and the vertical hydrometeor profiles that contribute to the associated cloud field.”

One year later, a study by Spencer and Braswell (2008) observed “our understanding of how sensitive the climate system is to radiative perturbations has been limited by large uncertainties regarding how clouds and other elements of the climate system feedback to surface temperature change (e.g., Webster and Stephens, 1984; Cess *et al.*, 1990; Senior and Mitchell, 1993; Stephens, 2005; Soden and Held, 2006; Spencer *et al.*, 2007).” The two scientists from the Earth System Science Center at the University of Alabama in Huntsville, Alabama then point out computer models typically assume that if the causes of internal sources of variability (X terms) are uncorrelated to surface temperature changes, then they will not affect the accuracy of regressions used to estimate the relationship between radiative flux changes and surface temperature (T). But “while it is true that the processes that cause the X terms are, by [Forster and Gregory (2006)] definition, uncorrelated to T , the response of T to those forcings cannot be uncorrelated to T —for the simple reason that it is a radiative forcing that causes changes in T .” They then ask, “to what degree could nonfeedback sources of radiative flux variability contaminate feedback estimates?”

In an attempt to answer this question, Spencer and Braswell used a “very simple time-dependent model of temperature deviations away from an equilibrium state” to estimate the effects of “daily random fluctuations in an unknown nonfeedback radiative source term N , such as those one might expect from stochastic variations in low cloud cover.” Repeated runs of the model found the diagnosed feedback departed from the true, expected feedback value of the radiative forcing, with the difference increasing as the amount of nonfeedback radiative flux noise was increased. “It is significant,” the authors write, “that all model errors for runs consistent with satellite-observed variability are in the direction of positive feedback, raising the possibility that current observational estimates of cloud feedback are biased in the positive direction.” In other words,

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as the authors report in their abstract, “current observational diagnoses of cloud feedback—and possibly other feedbacks—could be significantly biased in the positive direction.”

Writing as background for their work, Zhang *et al.* (2010) state different representations of clouds and their feedback processes in GCMs have been identified as major sources of differences in model climate sensitivities, noting “contemporary GCMs cannot resolve clouds and highly simplified parameterizations are used to represent the interactions between clouds and radiation.” In conducting their own study of the subject, therefore, they combine cloud profiling radar data from the CloudSat satellite with lidar data from the CALIPSO satellite to obtain 3D profiles of clouds and precipitation regimes across the tropics. Some of these profiles corresponded to well-known weather features, such as low clouds, thin cirrus, cirrus anvils, etc., and they were compared to output obtained from the Community Atmosphere Model version 3 (CAM3.1).

This analysis revealed the model “overestimates the area coverage of high clouds and underestimates the area coverage of low clouds in subsidence regions.” Zhang *et al.* found particularly striking “the model overestimate of the occurrence frequency of deep convection and the complete absence of cirrus anvils,” plus the fact that “the modeled clouds are too reflective in all regimes.”

Since incoming and outgoing radiation are strongly affected by the 3D spatial pattern of clouds of various types, a model that gets the “right” current global temperature with the wrong pattern of clouds must have errors in its radiation and/or heat transfer parameterizations. In addition, the manner in which future climate scenarios achieve amplification of the direct radiative effect of increased greenhouse gases (the assumed positive feedback) is also not likely to be correct if the 3D pattern of simulated clouds is as far off as shown in this study. What is more, the pattern of clouds also reflects convective processes that distribute heat and water vapor in the atmosphere, and the results of Zhang *et al.* point to deficiencies in the handling of this aspect of atmospheric dynamics as well. Climate modelers’ claims of physical realism in their models are not supported by detailed comparisons with the real world, and the basic radiative physics they employ, as parameterized at the grid scale, is probably faulty.

Shifting to a different aspect of the topic, climate modelers have long struggled to adequately represent

the sensitivity of convective cloud systems to tropospheric humidity in their mathematical representations of Earth’s climate system. Del Genio (2012) reviewed the rate of progress in this important endeavor in a paper published in the journal *Surveys in Geophysics*. The U.S. National Aeronautics and Space Administration scientist—stationed at the Goddard Institute for Space Studies in New York—found a number of important problems that have yet to be adequately resolved. He notes, for example, that many parameterizations of convective cloud variability “are not sufficiently sensitive to variations in tropospheric humidity.” That “lack of sensitivity,” as he describes it, “can be traced in part to underestimated entrainment of environmental air into rising convective clouds and insufficient evaporation of rain into the environment.” As a result of these deficiencies, he notes, “the parameterizations produce deep convection too easily while stabilizing the environment too quickly to allow the effects of convective mesoscale organization to occur.”

Del Genio does note “recent versions of some models have increased their sensitivity to tropospheric humidity and improved some aspects of their variability,” but he says “a parameterization of mesoscale organization is still absent from most models,” and “adequately portraying convection in all its realizations remains a difficult problem.”

On another note, Del Genio writes, “to date, metrics for model evaluation have focused almost exclusively on time mean two-dimensional spatial distributions of easily observed parameters,” and he indicates “it has become clear that such metrics have no predictive value for climate feedbacks and climate sensitivity (e.g., Collins *et al.*, 2011),” while adding those metrics “are also probably not helpful for assessing most other important features of future climate projections, because temporal variability gives greater insight into the physical processes at work.”

Del Genio concludes, “given the insensitivity of these models to tropospheric humidity and their failure to simulate the Madden-Julian Oscillation and diurnal cycle, ... it seems unlikely that it will ever be possible to establish a general set of metrics that can be used to anoint one subset of models as our most reliable indicators of all aspects of climate change.”

In another study, Cesana and Chepfer (2012) compare the most recent cloud representations of five of the climate models involved in the Coupled Model Intercomparison Project Phase 5 (CMIP5) effort described by Taylor *et al.* (2012) with real-world

satellite-derived observations obtained from the GCM-Oriented CALIPSO Cloud Product (GOCCP), described by Chepfer *et al.* (2010). According to Cesana and Chepfer, the results indicated: (1) “low- and mid-level clouds are underestimated by all the models (except in the Arctic),” (2) “high altitude cloud cover is overestimated by some models,” (3) “some models shift the altitude of the clouds along the ITCZ by 2 km (higher or lower) compared to observations,” (4) “the models hardly reproduce the cloud free subsidence branch of the Hadley cells,” (5) “the high-level cloud cover is often too large,” (6) “in the tropics, the low-level cloud cover (29% in CALIPSO-GOCCP) is underestimated by all models in subsidence regions (16% to 25%),” and (7) “the pronounced seasonal cycle observed in low-level Arctic clouds is hardly simulated by some models.”

Also writing in 2012, Li *et al.* (2012) state “representing clouds and cloud climate feedback in global climate models (GCMs) remains a pressing challenge,” but one that must be overcome in order “to reduce and quantify uncertainties associated with climate change projections.” Two of the primary parameters that must be accurately modeled in this regard are cloud ice water content (CIWC) and cloud ice water path (CIWP).

Li *et al.* performed, in their words, “an observationally based evaluation of the cloud ice water content and path of present-day GCMs, notably 20th century CMIP5 simulations,” after which they compared the results to two recent reanalyses. They used “three different CloudSat + CALIPSO ice water products and two methods to remove the contribution from the convective core ice mass and/or precipitating cloud hydrometeors with variable sizes and falling speeds so that a robust observational estimate can be obtained for model evaluations.”

The 11 U.S. scientists report, “for annual mean CIWP, there are factors of 2–10 in the differences between observations and models for a majority of the GCMs and for a number of regions,” and “systematic biases in CIWC vertical structure occur below the mid-troposphere where the models overestimate CIWC.” They ultimately conclude “neither the CMIP5 ensemble mean nor any individual model performs particularly well,” adding, “there are still a number of models that exhibit very large biases,” “despite the availability of relevant observations.” Even in cases where “the models may be providing roughly the correct radiative energy budget,” they state “many are accomplishing it by means of unrealistic cloud characteristics of cloud ice

mass at a minimum, which in turn likely indicates unrealistic cloud particle sizes and cloud cover.” Li *et al.* conclude “cloud feedback will undoubtedly still represent a key uncertainty in [even] the next IPCC assessment report.”

Cesana *et al.* (2012) state “low-level clouds frequently occur in the Arctic and exert a large influence on Arctic surface radiative fluxes and Arctic climate feedbacks,” noting that during winter, in particular, surface net longwave radiation ($F_{LW,NET}$) has a bimodal distribution, with extremes that have been termed “radiatively clear” and “radiatively opaque.” They note Arctic ice clouds “tend to have small optical depths and a weak influence on $F_{LW,NET}$,” which explains the “radiatively clear” condition, whereas Arctic liquid-containing clouds “generally have large optical depths and a dominant influence on $F_{LW,NET}$ (Shupe and Intrieri, 2004),” which explains the “radiatively opaque” condition, as discussed by Doyle *et al.* (2011).

Against this backdrop, Cesana *et al.* employed real-world Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data to document cloud phases over the Arctic basin (60–82°N) during the five-year period 2006–2011, after which they used the results they obtained “to evaluate the influence of Arctic cloud phase on Arctic cloud radiative flux biases in climate models.” The five researchers report their evaluation of climate models participating in the most recent Coupled Model Inter-comparison Project (Taylor *et al.*, 2012) revealed “most climate models are not accurately representing the bimodality of $F_{LW,NET}$ in non-summer seasons.” Even when advanced microphysical schemes that predict cloud phase have been used, such as those currently employed in the fifth version of the Community Atmosphere Model (CAM5, Neale *et al.*, 2010), “insufficient liquid water was predicted.”

Cesana *et al.* conclude “the simple prescribed relationships between cloud phase and temperature that have historically been used in climate models are incapable of reproducing the Arctic cloud phase observations described here,” which must inevitably lead to similarly inaccurate values of “Arctic surface radiative fluxes and Arctic climate feedbacks” when employed in current climate models.

Also focusing on low-level clouds were Nam *et al.* (2012), who write the response of low-level clouds has long been identified as “a key source of uncertainty for model cloud feedbacks under climate change,” citing the work of Bony and Dufresne (2005), Webb *et al.* (2006), Wyant *et al.* (2006), and

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Medeiros *et al.* (2008). They state “the ability of climate models to simulate low-clouds and their radiative properties” plays a large role in assessing “our confidence in climate projections.” Nam *et al.* analyzed “outputs from multiple climate models participating in the Fifth phase of the Coupled Model Intercomparison Project (CMIP5) using the Cloud Feedback Model Intercomparison Project Observations Simulator Package (COSP), and compared them with different satellite data sets,” including “CALIPSO lidar observations, PARASOL mono-directional reflectances, and CERES radiative fluxes at the top of the atmosphere.”

The comparison revealed “the current generation of climate models still experiences difficulties in predicting the low-cloud cover and its radiative effects.” In particular, they report the models: (1) “under-estimate low-cloud cover in the tropics,” (2) “over-estimate optical thickness of low-clouds, particularly in shallow cumulus regimes,” (3) “poorly represent the dependence of the low-cloud vertical structure on large-scale environmental conditions,” and (4) “predict stratocumulus-type of clouds in regimes where shallow cumulus cloud-types should prevail.” However, they say “the impact of these biases on the Earth’s radiation budget ... is reduced by compensating errors,” including “the tendency of models to under-estimate the low-cloud cover and to over-estimate the occurrence of mid- and high-clouds above low-clouds.”

Convective-type clouds and precipitation, especially when occurring over land areas, in the tropics, or during the warm season, have a strong diurnal cycle in phase with solar heating. People living in coastal regions are familiar with the diurnal cycle via the sea-breeze phenomenon. Unfortunately, models have difficulty representing the diurnal component of convection. Stratton and Stirling (2012) devised a better way to represent this phenomenon in an atmospheric general circulation model. In particular, they improved the rate at which environmental air and cloud air mix (entrainment). They also revised the mass flux over land in order to improve the timing and strength of convection influenced by diurnal heating.

In order to test the impact of the changes made to the diurnal convection scheme on the precipitation climatology of a model, Stratton and Stirling used a GCM with a horizontal resolution of less than two degrees in latitude and longitude and ran two ten-year simulations. The first was a control run with the model as it was provided to them. Then a ten-year run

was performed with the new convective parameterizations added. Results were compared with observed precipitation, as derived from output provided by the Tropical Rainfall Measurement Mission (TRMM) satellite.

According to the authors, the control run (Figure 1.3.4.1) “tends to lack precipitation over India and have too much precipitation over tropical land in Africa and in South America. The new run has generally reduced the precipitation over tropical land, tending to improve agreement with CMAP” (CMAP is an acronym for the observations). In the mid-latitudes though, there were regions (e.g., western Russia) where the new parameterization improved the model results, but other places where the new parameterization was worse (e.g., Europe). The results also did not noticeably alter the general circulation.

Stratton and Stirling improved the attendant physics associated with convection and in general improved the climatological representation of precipitation. But there were still differences in comparison with observed precipitation. In some regions, the new convective scheme performance was not as good. Improvement was not uniform, even though the model was overall closer to reality.

The new parameterizations may have done a good job of representing precipitation over short time-scales, but over longer time-scales it still did not represent the climatology of precipitation very well.

Ahlgrimm and Forbes (2012) investigated an irradiance bias in the European Centre for Medium Range Forecasting (ECMWF) GCM, focusing on the Southern Great Plains of the USA. This GCM was built to generate daily weather predictions. In one experiment, the authors compared measured radiation daily in 2004–2009 from the Atmospheric Radiation Measurement Site (ARM) in the Southern Great Plains (SGP) (Figure 1.3.4.2). In the second, they compared the ECMWF model output to observations of clouds, radiation, and the state of the atmosphere archived as the Climate Modelling Best Estimate product from 1997–2009. Ahlgrimm and Forbes selected 146 days when fair weather cumulus clouds dominated the Southern Great Plains. They compared these to the same days run using the ECMWF model initialized the day before and using the 18–42 hour forecasts.

The results indicate the mean model radiative bias compared to the observed product was approximately 23 W m^{-2} . When the authors looked at the fair weather cumulus regime and studied the bias over the

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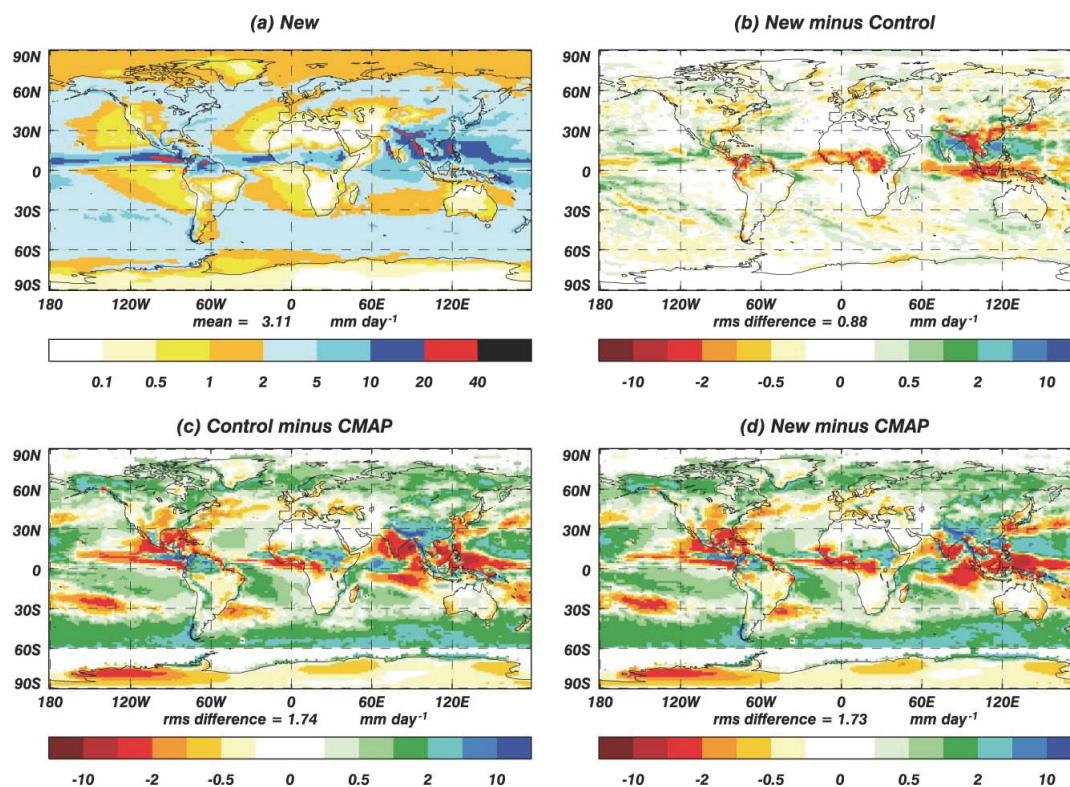


Figure 1.3.4.1. The mean summer season precipitation for (a) new convective climatology, (b) new run minus the control, (c) control minus CMAP (observations), (d) new run minus CMAP. Reprinted with permission from Stratton, R.A. and Stirling, A.J. 2012. Improving the diurnal cycle of convection in GCMs. *Quarterly Journal of the Royal Meteorological Society* **138**: 1121–1134, Figure 3.

course of a day, they found the bias in this regime was weak. This means the parameterizations for fair weather convective cloudiness were largely successful. When the authors attempted to classify clouds, they found the deep clouds (convective), thick mid-level clouds, and low clouds as a group accounted for more than 50 percent of the bias. As there was no way to account for high clouds and other phenomena, the remaining bias was simply referred to as “residual.” They also demonstrated refinements in the cloud liquid water content and distributions could improve these parameterizations.

Lastly, Alhgrimm and Forbes showed the biases are largest when the observations were cloudy and the model clear, or when the observations were overcast and the model produced broken skies. All other categories showed small biases that largely cancelled each other out. The two researchers conclude, “it will be possible to carry out targeted sensitivity studies to improve cloud occurrence and radiative properties by examining the formulation of the shallow convection trigger, mass transport, and cloud microphysical

properties.” If there is a net positive bias in shortwave reaching the surface, it will result in the overestimation of temperatures in the two situations described above and overall. If these parameterizations, or others that produce warm biases, are used in climate models, the impact on climate scenarios would be a net surface warming.

Grodsky *et al.* (2012) point out “the seasonal climate of the tropical Atlantic Ocean is notoriously difficult to simulate accurately in coupled models,” noting a long history of studies, including those of Zeng *et al.* (1996), Davey *et al.* (2002), Deser *et al.* (2006), Chang *et al.* (2007), and Richter and Xie (2008), “have linked the ultimate causes of the persistent model biases to problems in simulating winds and clouds by the atmospheric model component.” In an effort designed to “revisit” this unsolved problem, Grodsky *et al.* utilized the Community Climate System Model, version 4 (CCSM4; Gent *et al.*, 2011), a coupled climate model that simultaneously simulates Earth’s atmosphere, ocean, land surface, and sea ice processes. They did

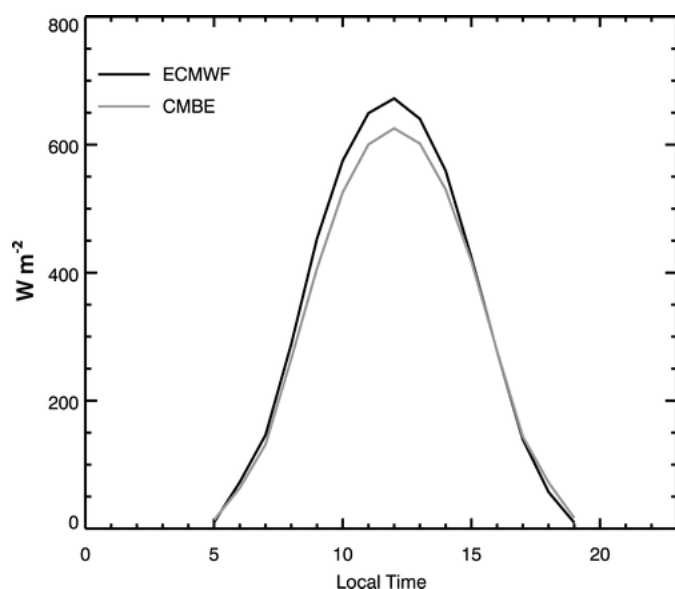


Figure 1.3.4.2. The multiyear (2004–09) all-sky diurnal composite of surface irradiance. The black line is the ECMWF model, and the grey line is the observations from the CMBE product. Only daytime samples (modelled short wave down exceeding 1 W m^{-2}) with good-quality coincident observations are included. Reprinted with permission from Ahlgrimm, M. and Forbes, R. 2012. The impact of low clouds on surface shortwave radiation in the ECMWF model. *Monthly Weather Review* **140**: 3783–3794, Figure 1.

so by comparing twentieth century runs forced by time-varying solar output, greenhouse gas, and volcanic and other aerosol concentrations for the period 1850–2005 with observed (real world) monthly variability computed from observational analyses during the 26-year period 1980–2005.

The four researchers report finding (1) the “atmospheric component of CCSM4 has abnormally intense surface subtropical high pressure systems and abnormally low polar low pressure systems,” (2) “in the tropics and subtropics, the trade wind winds are 1–2 m/sec too strong [and] latent heat loss is too large,” (3) “sea surface temperature in the southeast has a warm bias [due in part to] erroneously weak equatorial winds,” (4) “the warm bias evident along the coast of southern Africa is also partly a result of insufficient local upwelling,” (5) “excess radiation is evident in the south stratocumulus region of up to 60 W/m^2 ,” (6) there is “excess precipitation in the Southern Hemisphere,” and (7) “errors in cloud parameterization lead to “massively excess solar radiation in austral winter and spring in CCSM4.”

It is clear that many important aspects of clouds and cloud cover remain inadequately modeled. The

cloud parameterization problem is extremely complex and will likely remain that way for the foreseeable future.

Writing in the *Journal of Geophysical Research (Atmospheres)*, Wang and Su (2013) note “coupled general circulation models (GCMs) are the major tool to predict future climate change, yet cloud-climate feedback constitutes the largest source of uncertainty in these modeled future climate projections.” Thus they state “our confidence in the future climate change projections by the coupled GCMs to a large extent depends on how well these models simulate the observed present-day distribution of clouds and their associated radiative fluxes.” About their own work, they write, “the annual mean climatology of top of the atmosphere (TOA) shortwave and longwave cloud radiative effects in 12 Atmospheric Model Intercomparison Project (AMIP)-type simulations participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) [was] evaluated and investigated using satellite-based observations, with a focus on the tropics.”

The two researchers report the CMIP5 AMIPs “produce considerably less cloud amount [than what is observed], particularly in the middle and lower troposphere.” Moreover, there are “good model simulations in tropical means,” but they are “a result of compensating errors over different dynamical regimes.” “Over the Maritime Continent,” they note, “most of the models simulate moderately less high-cloud fraction, leading to weaker shortwave cooling and longwave warming and a larger net cooling,” while “over subtropical strong subsidence regimes, most of the CMIP5 models strongly underestimate stratocumulus cloud amount and show considerably weaker local shortwave cloud radiative forcings,” and “over the transitional trade cumulus regimes, a notable feature is that while at varying amplitudes, most of the CMIP5 models consistently simulate a deeper and drier boundary layer, more moist free troposphere, and more high clouds and consequently overestimate shortwave cooling and longwave warming effects there.” They conclude, “representing clouds and their TOA radiative effects remains a challenge in the CMIP5 models.”

In a revealing paper published in the American Meteorological Society’s *Journal of Climate*, Lauer and Hamilton (2013) report numerous previous studies from the Coupled Model Intercomparison Project phase 3 (CMIP3) showed large biases in the simulated cloud climatology affecting all GCMs, as well as “a remarkable degree of variation among the

models that represented the state of the art circa 2005.” The two researchers set out to provide an update by describing the progress that has been made in recent years by comparing mean cloud properties, interannual variability, and the climatological seasonal cycle from the CMIP5 models with results from comparable CMIP3 experiments, as well as with actual satellite observations.

Lauer and Hamilton conclude “the simulated cloud climate feedbacks activated in global warming projections differ enormously among state-of-the-art models,” while noting “this large degree of disagreement has been a constant feature documented for successive generations of GCMs from the time of the first Intergovernmental Panel on Climate Change assessment through the CMIP3 generation models used in the fourth IPCC assessment.” They add, “even the model-simulated cloud climatologies for present-day conditions are known to depart significantly from observations and, once again, the variation among models is quite remarkable (e.g., Weare, 2004; Zhang *et al.*, 2005; Waliser *et al.*, 2007, 2009; Lauer *et al.*, 2010; Chen *et al.*, 2011).”

The two researchers determined (1) “long-term mean vertically integrated cloud fields have quite significant deficiencies in all the CMIP5 model simulations,” (2) “both the CMIP5 and CMIP3 models display a clear bias in simulating too high LWP [liquid water path] in mid-latitudes,” (3) “this bias is not reduced in the CMIP5 models,” (4) there have been “little to no changes in the skill of reproducing the observed LWP and CA [cloud amount],” (5) “inter-model differences are still large in the CMIP5 simulations,” and (6) “there is very little to no improvement apparent in the tropical and subtropical regions in CMIP5.”

Lauer and Hamilton indicate there is “only very modest improvement in the simulated cloud climatology in CMIP5 compared with CMIP3,” adding even this slightest of improvements “is mainly a result of careful model tuning rather than an accurate fundamental representation of cloud processes in the models.”

It would therefore appear, given the findings described in this section, that the outlook for adequately modeling clouds and cloud processes must still be characterized as cloudy.

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1.3.5 Precipitation

1.3.5.1 Precipitation

Correctly simulating future precipitation has proven to be an extremely difficult task for modelers. One reason for the lack of success in this area is inadequate model resolution on both vertical and horizontal spatial scales, a limitation that forces climate modelers to parameterize the large-scale effects of processes (such as deep convection, which is the source of most precipitation) that occur on smaller scales than the models are capable of simulating. But there are other problems as well that result in vast differences between model projections and real-world observations. This section documents such problems and variances as they relate to model projections of precipitation.

In an early study of the subject, Lebel *et al.* (2000) compared rainfall simulations produced by a GCM with real-world observations from West Africa for the period 1960–1990. Their analysis revealed the model output was affected by a number of temporal and spatial biases that led to significant differences between observed and modeled data. The simulated rainfall totals, for example, were significantly greater than what was typically observed, exceeding real-world values by 25 percent during the dry season and 75 percent during the rainy season. In addition, the seasonal cycle of precipitation was not well simulated, as the researchers found the simulated rainy season began too early and the increase in precipitation was not rapid enough. Shortcomings were also evident in the GCM's inability to accurately simulate convective rainfall events, as it typically predicted too much precipitation. Furthermore, it was

found “inter-annual variability [was] seriously disturbed in the GCM as compared to what it [was] in the observations.” As for why the GCM performed so poorly in these several respects, Lebel *et al.* gave two main reasons: parameterization of rainfall processes in the GCM was much too simple, and spatial resolution was much too coarse.

Lau *et al.* (2006) considered the Sahel drought of the 1970s–1990s to provide “an ideal test bed for evaluating the capability of CGCMs [coupled general circulation models] in simulating long-term drought, and the veracity of the models' representation of coupled atmosphere-ocean-land processes and their interactions.” They chose to “explore the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4,” in which the 19 CGCMs “are 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 climate scientists found “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, they report, “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.” All 19 of the CGCMs employed in the IPCC's *Fourth Assessment Report*, in other words, failed to adequately simulate the basic characteristics of “one of the most pronounced signals of climate change” of the past century—as defined by its start date, severity and duration.”

Writing in *Science*, Wentz *et al.* (2007) noted the Coupled Model Intercomparison Project, as well as various climate modeling analyses, predicted an increase in precipitation on the order of 1 to 3 percent per °C of surface global warming. They decided to see what had happened in the real world in this regard over the prior 19 years (1987–2006) of supposedly unprecedented global warming, when data from the Global Historical Climatology Network and satellite measurements of the lower troposphere indicated there had been a global temperature rise on the order of 0.20°C per decade.

Using satellite observations obtained from the

Special Sensor Microwave Imager (SSM/I), the four Remote Sensing Systems scientists derived precipitation trends for the world's oceans over this period. Using data obtained from the Global Precipitation Climatology Project acquired from both satellite and rain gauge measurements, they derived precipitation trends for Earth's continents. Combining the results of these two endeavors, they derived a real-world increase in precipitation on the order of 7 percent per °C of surface global warming, somewhere between 2.3 and 7.0 times larger than what is predicted by state-of-the-art climate models.

How was this discrepancy to be resolved? Wentz *et al.* conclude the only way to bring the two results into harmony was for there to have been a 19-year decline in global wind speeds. But when looking at the past 19 years of SSM/I wind retrievals, they found just the opposite, an increase in global wind speeds. In quantitative terms, the two results were about as opposite as they could possibly be: “when averaged over the tropics from 30°S to 30°N, the winds increased by 0.04 m s⁻¹ (0.6 percent) decade⁻¹, and over all oceans the increase was 0.08 m s⁻¹ (1.0 percent) decade⁻¹,” while global coupled ocean-atmosphere models or GCMs, in their words, “predict that the 1987-to-2006 warming should have been accompanied by a decrease in winds on the order of 0.8 percent decade⁻¹.”

Wentz *et al.* state, “the reason for the discrepancy between the observational data and the GCMs is not clear.” They also observe this dramatic difference between the real world of nature and the virtual world of climate modeling “has enormous impact” and the questions raised by the discrepancy “are far from being settled.”

In a separate paper published that year, Allan and Soden (2007) quantified trends in precipitation within ascending and descending branches of the planet's tropical circulation and compared their results with simulations of the present day and projections of future changes provided by up to 16 state-of-the-art climate models. The precipitation data for this analysis came from the Global Precipitation Climatology Project (GPCP) of Adler *et al.* (2003) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) data of Xie and Arkin (1998) for the period 1979–2006, while for the period 1987–2006 the data came from the monthly mean intercalibrated Version 6 Special Sensor Microwave Imager (SSM/I) precipitation data described by Wentz *et al.* (2007).

The researchers report “an emerging signal of

rising precipitation trends in the ascending regions and decreasing trends in the descending regions are detected in the observational datasets,” but “these trends are substantially larger in magnitude than present-day simulations and projections into the 21st century,” especially in the case of the descending regions. More specifically, for the tropics “the GPCP trend is about 2–3 times larger than the model ensemble mean trend, consistent with previous findings (Wentz *et al.*, 2007) and also supported by the analysis of Yu and Weller (2007),” who additionally contended “observed increases of evaporation over the ocean are substantially greater than those simulated by climate models.” In addition, Allan and Soden note “observed precipitation changes over land also appear larger than model simulations over the 20th century (Zhang *et al.*, 2007).”

Noting the difference between the models and real-world measurements “has important implications for future predictions of climate change,” Allan and Soden state “the discrepancy cannot be explained by changes in the reanalysis fields used to subsample the observations but instead must relate to errors in the satellite data or in the model parameterizations.” This dilemma also was faced by Wentz *et al.* (2007), and they too state the resolution of the issue “has enormous impact” and likewise conclude the questions raised by the discrepancy “are far from being settled.”

According to Lin (2007), “a good simulation of tropical mean climate by the climate models is a prerequisite for their good simulations/predictions of tropical variabilities and global teleconnections,” but “unfortunately, the tropical mean climate has not been well simulated by the coupled general circulation models (CGCMs) used for climate predictions and projections.” They note “most of the CGCMs produce a double-intertropical convergence zone (ITCZ) pattern” and they acknowledge “a synthetic view of the double-ITCZ problem is still elusive.”

Lin analyzed tropical mean climate simulations of the 20-year period 1979–1999 provided by 22 IPCC *Fourth Assessment Report* CGCMs, together with concurrent Atmospheric Model Intercomparison Project (AMIP) runs from 12 of them. This revealed, in Lin's words, that “most of the current state-of-the-art CGCMs have some degree of the double-ITCZ problem, which is characterized by excessive precipitation over much of the Tropics (e.g., Northern Hemisphere ITCZ, Southern Hemisphere SPCZ [South Pacific Convergence Zone], Maritime Continent, and equatorial Indian Ocean), and often

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associated with insufficient precipitation over the equatorial Pacific,” as well as “overly strong trade winds, excessive LHF [latent heat flux], and insufficient SWF [shortwave flux], leading to significant cold SST (sea surface temperature) bias in much of the tropical oceans.”

Lin further notes “most of the models also simulate insufficient latitudinal asymmetry in precipitation and SST over the eastern Pacific and Atlantic Oceans,” and “the AMIP runs also produce excessive precipitation over much of the Tropics including the equatorial Pacific, which also leads to overly strong trade winds, excessive LHF, and insufficient SWF.” All of this suggests “the excessive tropical precipitation is an intrinsic error of the atmospheric models,” Lin writes, adding, “over the eastern Pacific stratus region, most of the models produce insufficient stratus-SST feedback associated with insufficient sensitivity of stratus cloud amount to SST.”

With the solutions to all of these longstanding problems continuing to remain “elusive,” and with Lin suggesting the sought-for solutions are in fact prerequisites for “good simulations/predictions” of future climate, there is significant reason to conclude that current state-of-the-art CGCM predictions of CO₂-induced global warming should not be considered reliable.

Lavers *et al.* (2009) examined the predictive skill of eight seasonal climate forecast models developed at various European climate centers. Specifically, they assessed the predictability of monthly precipitation “retrospective forecasts” or hindcasts, composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001. They compared the projections against real-world precipitation values obtained from Global Precipitation Climatology Center data. In addition, they conducted a virtual-world analysis, where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

These analyses indicate that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where the models had negligible skill over land at a 31-day lead time, which the researchers describe as being “a relatively short lead time in terms of seasonal climate prediction.” The three researchers

conclude that given the lack of real-world skill demonstrated by models, “it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers,” a quest they frankly state “may prove to be elusive.”

Anagnostopoulos *et al.* (2010) compared observed versus modeled precipitation values over the twentieth century for 55 locations across the globe. Their results indicate the six models investigated (three from the IPCC’s *Third Assessment* and three from its *Fourth Assessment*) reproduced only poorly the observed precipitation values over the period of study. In far too many instances the models showed a rise in precipitation when observed values actually fell, or vice versa. The models fared worse when a similar analysis was conducted in the aggregate for the entire conterminous United States. Model output differed “substantially” from the observed time series, with annual precipitation values overestimating observed values by up to 300 mm, or 40 percent. The authors also state the results from the three models used in the IPCC’s *Fourth Assessment Report* were “no better” than the three models used in the IPCC’s *Third Assessment Report*.

Ault *et al.* (2012) write “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,” noting specifically “CMIP3 simulations overestimated the magnitude of high frequency fluctuations and consequently underestimated the risk of future decadal-scale droughts.” Since “a new generation of coupled general circulation models (GCMs) has been developed and made publicly available as part of the Climate Model Intercomparison Project 5 (CMIP5) effort,” it is critical, the note, “to evaluate the ability of these models to simulate realistic 20th century variability regionally and across a variety of timescales.”

Using gridded (2.5 x 2.5) version 4 reanalysis product data made available to them by the Global Precipitation Climatology Centre (Rudolf *et al.*, 2005)—which spanned the period January 1901 through December 2007—Ault *et al.* assessed the magnitude of D2M variability in new CMIP5 simulations. The three U.S. researchers report their results suggest “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 (Cai *et al.*, 2009; 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 that 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.”

Aaliser *et al.* (2011) write, “key to the proper use of satellite retrievals in the evaluation of modeled cloud ice and liquid is that many global climate model representations ignore or diagnostically treat the falling hydrometeor components (e.g., rain and snow) and only consider—for the purposes of radiation calculations—the ‘suspended’ component of water that the model deems ‘clouds.’” They state “the variations in the annual mean integrated ice water path and liquid water path between global climate models contributing to the IPCC AR4 range over two orders of magnitude,” citing Li *et al.* (2008) and Waliser *et al.* (2009). Employing estimates of cloud and precipitating ice mass and characterizations of its vertical structure supplied by CloudSat retrievals, Waliser *et al.* set out to perform radiative transfer calculations “to examine the impact of excluding precipitating ice on atmospheric radiative fluxes and heating rates.”

According to the four researchers, the exclusion of precipitating ice “can result in underestimates of the reflective shortwave flux at the top of the atmosphere (TOA) and overestimates of the downwelling surface shortwave and emitted TOA longwave flux, with the differences being about 5–10 Wm^{-2} in the most convective and rainfall intensive areas.” In addition, they report, “there are also considerable differences (~10-25%) in the vertical profiles of shortwave and longwave heating, resulting in an overestimation (~up to 10%) of the integrated column cooling.” And they state “the magnitude of these potential errors is on the order of the radiative heating changes associated with a doubling of atmospheric carbon dioxide.”

With respect to the implications of their findings,

Waliser *et al.* state “when the above results are considered in the context of a climate model simulation, the changes would not only impact the radiative heating of the atmosphere but would be expected to impact the circulation, and possibly even the manner the model adjusts to external forcings such as increasing greenhouse gases.” In addition, they note, since the “models are tuned to get the right TOA radiation balance, the implications here are that without considering the ice in precipitating hydrometeors explicitly, the models will be getting the right result (i.e., TOA balance) for the wrong reasons,” and “in doing so, there are likely to be compensating errors in other quantities such as cloud cover, cloud particle effective radius and/or cloud mass.”

In another paper, Soncini and Bocchiola (2011) note “General Circulation Models (GCMs) are widely adopted tools to achieve future climate projections.” However, they write, “one needs to assess their accuracy, which is only possible by comparison of GCMs’ control runs against past observed data,” which they proceeded to do in the case of snowfall regimes within the Italian Alps. Specifically, the two Italian researchers investigated the accuracy of simulations of snowfall throughout the Italian Alps provided by two GCMs (HadCM3, CCSM3), which are included within the family of models employed by the IPCC. This was done by comparing the models’ output with a set of comprehensive ground data obtained from some 400 snow-gauging stations located within the region of interest for the period 1990–2009.

In examining the model versus observation comparison, Soncini and Bocchiola determined “the investigated GCMs provide poor depiction of the snowfall timing and amount upon the Italian Alps,” noting, in fact, the HadCM3 model actually “displays considerable snowfall during summer,” which they indicate “is clearly not supported by ground data.” In addition, they report obtaining “contrasting results between the two models,” with HadCM3 providing substantially constant volumes of snow received over time and CCSM3 projecting decreasing snowfall volumes. “Overall,” in the words of the two researchers, “given the poor depiction of snowfall by the GCMs here tested, we suggest that care should be taken when using their outputs for predictive purposes.”

Also investigating snowfall were Salzmann and Mearns (2012), who note “climate impact assessments require primarily regional- to local-scale

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climate data for the past and the present and scenarios for the future,” stating, with respect to the future, that “regional climate models (RCMs) are among the most promising tools to simulate climate on the regional scale.” However, they also note “the effective benefit of each of these RCMs and their ensembles for specific climate impact assessments remains to be proven for individual impact studies.” Salzmänn and Mearns explore this issue within the context of the North American Regional Climate Change Program (NARCCAP; Mearns *et al.*, 2009) with regard to the seasonal snow regime in the Upper Colorado River Basin. They compared NARCCAP results with *in situ* observations and data obtained from various reanalysis projects.

The two researchers at the National Center for Atmospheric Research in Boulder, Colorado (USA) report—quite bluntly and to the point: “[T]he RCMs are generally too dry, too warm, simulate too little snow water equivalent, and have a too-short snow cover duration with a too-late start and a too-early end of a significant snow cover.” To these problems they add, “attributing the found biases to specific features of the RCMs remains difficult or even impossible without detailed knowledge of the physical and technical specification of the models.”

Stewart *et al.* (2011) write, “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). In an exercise designed to assess the reasonableness of these projections, Stewart *et al.* 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 uncovering pertinent data from the period they investigated that suggests “an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June–July–August temperatures,” which further suggests—as they also note—the frequency of flooding “was reduced during warm and/or dry climates.” In 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,” pretty much debunking the projections of regional climate models that have suggested otherwise.

Soares *et al.* (2012) note “Regional Climate Models (RCMs) are increasingly used to assess the impact of climate change at regional and local scales (Giorgi and Mearns, 1999; Wang *et al.*, 2004; Christensen and Christensen, 2007),” because “in regions where local features affecting the atmospheric flow, such as topography and coastal processes, are prevalent, finer resolution simulations with state-of-the-art mesoscale models are required to reproduce observed weather and climate (Mass *et al.*, 2002; Salathé *et al.*, 2008).” They utilized “a new data set of daily gridded observations of precipitation, computed from over 400 stations in Portugal, to assess the performance of 12 regional climate models at 25-km resolution, from the ENSEMBLES set, all forced by ERA-40 boundary conditions, for the 1961–2000 period,” while “standard point error statistics, calculated from grid point and basin aggregated data, and precipitation related climate indices are used to analyze the performance of the different models in representing the main spatial and temporal features of the regional climate, and its extreme events.”

Although the five Portuguese researchers say the models achieved what they called a “good representation” of the features listed above, they also list a number of less-than-hoped-for results: (1) “10 of the 12 analyzed models under-predict Portuguese precipitation,” (2) “half of the models under-represent observed variability of daily precipitation,” (3) “models were found to underestimate the number of wet days,” (4) “grid point percentiles of precipitation are generally under-predicted,” (5) “in all cases, there is a significant model spread,” (6) “the 95th percentile is under-predicted by all models in most of the country,” and (7) “there is an important model spread in all analyzed variables.” Such findings led Soares *et al.* to state in their concluding paragraph, “the present results suggest that there is still some way to go in this research.”

Focusing on a nearby region, Kelley *et al.* (2012) state “winter and summer Mediterranean precipitation climatology and trends since 1950 as simulated by the

newest generation of global climate models, the Coupled Model Intercomparison Project phase 5 (CMIP5), [were] evaluated with respect to observations and the previous generation of models (CMIP3) used in the Intergovernmental Panel on Climate Change Fourth Assessment Report,” with the objective of determining “to what extent we can trust the multi-model mean (MMM) trends as representing the externally forced trends.” Upon analysis, Kelly *et al.* determined “the Mediterranean precipitation trends of the last half century in the CMIP5 MMMs and the observations differ significantly, particularly in winter and over the northern Mediterranean region.” The CMIP5 MMM trend, for example, “indicates a modest drying throughout the seasonal cycle, with the strongest drying in the March, April and May spring season.” The observed trend, on the other hand, “shows a predominantly winter drying,” and they state “it is not entirely clear what causes this discrepancy.”

Although the four researchers report “there is a modest improvement of the CMIP5 climatology over CMIP3,” it would appear “modest” is too generous a word to describe what was accomplished between the development of the CMIP3 and CMIP5 models, particularly given their conclusion that the slight improvement they detected may have been due merely to the “improved horizontal resolution” of the CMIP5 models. The ultimate implication of Kelly *et al.*’s findings is presented in the concluding paragraph of their paper, where they state their findings “reinforce the need for further research and better understanding of the mechanisms driving the region’s hydroclimate.”

Also working in the Mediterranean region, Barkhordarian *et al.* (2013) assessed the role of anthropogenic forcing due to greenhouse gases and sulphate aerosols (GS) in recently observed precipitation trends over the Mediterranean region in order to determine whether the observed trends over the period 1966–2005 (over land) and 1979–2008 (over land and sea) “are consistent with what 22 models project as response of precipitation to GS forcing,” where “significance is estimated using 9,000-year control runs derived from the CMIP3 archive.”

The three researchers discovered “the observed trends are markedly inconsistent with expected changes due to GS forcing,” as “observed changes are several times larger than the projected response to GS forcing in the models.” But they state “the most striking inconsistency” was “the contradiction

between projected drying and the observed increase in precipitation in late summer and autumn.” Coming to a conclusion that cannot be avoided, Barkhordarian *et al.* therefore state “the detection of an outright sign mismatch of observed and projected trends in autumn and late summer, leads us to conclude that the recently observed trends cannot be used as an illustration of plausible future expected change in the Mediterranean region,” once again illustrating the many problems besetting even the best of climate models.

In another paper, Miao *et al.* (2012) assessed the performance of the AR4 GCMs (CMIP3 models) in simulating precipitation and temperature in China from 1960 to 1999 by comparing the model simulations with observed data, using “system bias (*B*), root-mean-square error (*RMSE*), Pearson correlation coefficient (*R*) and Nash-Sutcliffe model efficiency (*E*)” as evaluation metrics. The four researchers conclude certain of the CMIP3 models “are unsuitable for application to China, with little capacity to simulate the spatial variations in climate across the country,” adding all of them “give unsatisfactory simulations of the inter-annual temporal variability.” In addition, they found “each AR4 GCM performs differently in different regions of China.” In light of these findings, Miao *et al.* conclude “the inter-annual simulations (temperature and precipitation) by AR4 GCMs are not suitable for direct application,” and “caution should be applied when using outputs from the AR4 GCMs in hydrological and ecological assessments” because of their “poor performance.”

Kataoka *et al.* (2012) note the Indian Ocean Subtropical Dipole (IOSD; Behera *et al.*, 2000; Behera and Yamagata, 2001) is “one of the climate modes that generate climate variations in the Southern Hemisphere,” having “a great impact on the surrounding countries through its influence on the rainfall (Behera and Yamagata, 2001; Reason, 2001; Washington and Preston, 2006).” This mode is characterized by “a dipole pattern in the sea surface temperature anomaly in the southern Indian Ocean with a warm (cold) southwestern pole and cold (warm) northeastern pole during austral summer.” “[S]ince southern Africa is one of the most vulnerable regions to abnormal weather events,” they note, “an accurate prediction of the IOSD together with its influence on rainfall is necessary to mitigate the impacts.” Using observational data and mathematical outputs from 22 coupled general circulation models (CGCMs) submitted to the World Climate Research

Programme's Coupled Model Intercomparison Project phase 3 (CMIP3), Kataoka *et al.* proceeded to assess each model's ability to simulate the IOSD and its influence on rainfall anomalies over southern Africa.

In discussing their findings, the four Japanese researchers report the location and orientation of sea surface temperature anomaly poles "differ considerably" from one model to another, owing primarily to model biases in sea level pressure anomalies. This finding, as they describe it, supports "the earlier results of Morioka *et al.* (2010) based on an ocean general circulation model." This problem, in their words, "may partly explain the poor skills of CGCMs in simulating the influence of the IOSD on the rainfall anomalies." In addition, they state "some models fail to simulate the statistical relation between the positive (negative) rainfall anomaly and La Niña (El Niño)." The authors conclude "more accurate simulation of the IOSD as well as the influence of the ENSO is necessary to improve the seasonal prediction of southern African rainfall."

According to Jiang *et al.* (2013), "multi-scale temporal variability of precipitation has an established relationship with floods and droughts," and GCMs can provide "important avenues to climate change impact assessment and adaptation planning," but only if they possess an "ability to capture the climatic variability at appropriate scales." Jiang *et al.* assessed "the ability of 16 GCMs from the Bias Corrected and Downscaled (BCSD) World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) projections and 10 Regional Climate Models (RCMs) that participated in the North American Regional Climate Change Assessment Program (NARCCAP) to represent multi-scale temporal variability determined from observed station data." They focused on four regions in the Southwest United States—Los Angeles, Las Vegas, Tucson, and Cimarron—because these places "represent four different precipitation regions classified by clustering method." They specifically investigated "how storm properties and seasonal, inter-annual, and decadal precipitation variabilities differed between GCMs/RCMs and observed records in these regions."

The four U.S. researchers report "RCMs tend to simulate [1] longer duration, [2] shorter inter-storm periods, and [3] lower storm intensity than observed." Moreover, they state [4] "RCMs fail to simulate high average storm intensity during the summer period as seen in observed precipitation records." They also say

[5] bias-corrected and downscaled GCMs "lack the ability to reproduce observed monthly precipitation patterns." In addition, they note "observed precipitation tends to be above average during the PDO warm phase, while precipitation during the PDO cold phase is below average," and [6] "most of the considered GCMs failed to reproduce similar variability." Their wavelet analysis revealed [7] "even the successful GCMs on reproducing the low-frequency variability associated with ENSO and PDO, showed inconsistency in the occurrence or timing of 2–8-year bands." Jiang *et al.* conclude their "comparative analyses suggest that current GCMs/RCMs do not adequately capture multi-scale temporal variability of precipitation," and, therefore, "using GCM/RCM output to conduct future flood projections is not creditable."

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1.4.5.2 Monsoons

Climate modelers have long struggled to simulate seasonal monsoons despite their significance in global climate. As mentioned in a prior section of this chapter, when the 2004 summer monsoon season of India experienced a 13 percent deficit not predicted by either empirical or dynamical models used in making rainfall forecasts, Gadgil *et al.* (2005) decided to perform a historical analysis of the models' skills over the period 1932 to 2004. They found despite numerous model changes and an ever-improving understanding of monsoon variability, Indian monsoon model forecasting skill had not improved since 1932. Large differences often were observed when comparing monsoon rainfall measurements with empirical model predictions; and the models often failed to correctly predict even the *sign* of the precipitation anomaly.

Dynamical models fared even worse. In comparing observed versus predicted monsoon rainfall from 20 atmospheric general circulation models and one supposedly superior coupled atmosphere-ocean model, Gadgil *et al.* report none was able “to simulate correctly the interannual variation of the summer monsoon rainfall over the Indian region.” Like the empirical models, they frequently failed to simulate not only the magnitude but also the sign of the real-world rainfall anomalies. Few improvements seem to have occurred since that time.

Zhang *et al.* (2012) report “the Asian monsoon is a major component in the global climate system, characterized by remarkable seasonal and inter-annual rainfall variations which have significant social and economic influences on large populations in the region,” the complexity of which, in their words, “is never overstated.” Using daily precipitable water and 850 hPa monsoon wind data, which in the words of Zhang *et al.* “represent large-scale moisture and

dynamic conditions for monsoon development,” the four scientists analyzed “potential changes in Asian monsoon onset, retreat and duration simulated by 13 IPCC AR4 models.”

The Chinese-Australian research team report there “is no single outstanding model out of the 13 models used in the analysis,” noting “some of the models have shown significant biases in mean onset/retreat dates and some failed to produce the broad features of how [the] monsoon evolves.” Over East Asian land, for example, they found “the models are nearly equally divided about the sign of potential changes of onset/retreat.” And, sounding rather frustrated, they lament 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,” adding “it is unclear what are the key parameterizations leading to the differences in simulating ENSO and its responses to global warming,” citing Solomon *et al.* (2007) and Wang *et al.* (2009). They 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.”

In another study, Kim *et al.* (2012) note “the Asian monsoon influences almost half of the world’s population with their agriculture, life and society depending on monsoon climate” and, therefore, “understanding the physical processes that determine the character of the monsoon systems and also providing accurate extended range predictions on a seasonal timescale is crucial for the economy and policy planning in the monsoon regions.”

Kim *et al.* assessed the seasonal prediction skill regarding the Asian summer monsoon via the use of “retrospective predictions (1982–2009) from the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) seasonal prediction systems.” The four researchers state, “in both SYS4 and CFSv2, a cold bias of sea-surface temperature (SST) is found over the Equatorial Pacific, North Atlantic [and] Indian Oceans,” as well as “over a broad region in the Southern Hemisphere relative to observations,” and “a warm bias is found over the northern part of the North Pacific and North Atlantic.” In addition, they state “excessive precipitation is found along the Intertropical Convergence Zone, equatorial Atlantic, equatorial Indian Ocean and the maritime continent.” And they find “the southwest monsoon flow and the 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.” With both of the world’s most advanced climate modeling systems “performing poorly,” in the estimation of Kim *et al.*, in simulating monsoon precipitation that affects almost half of the world’s population, it would appear the climate modeling enterprise has a long way to go before confidence can be placed in its projections, whether under CO₂ forcing or otherwise.

Wu and Zhou (2013) sought to evaluate the performance of the Flexible Global Ocean-Atmosphere-Land System model, Spectral Version 2 (FGOALS-s2)—a CGCM developed by the National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics of the Chinese Academy of Sciences—with respect to its ability to simulate the relationship between ENSO and the East Asian-western North Pacific (EA-WNP) monsoon. The two authors write, “after nearly five years of effort,” the original model (Wu *et al.*, 2009) “has been improved in various facets” and it was therefore necessary “to carefully assess the ENSO-monsoon relationship in the current version of the model.”

Wu and Zhou noted several problems with the model: it “fails to simulate the asymmetry of the wintertime circulation anomalies over the WNP between El Niño and La Niña”; “the simulated anomalous cyclone over the WNP (WNPAC) associated with La Niña is generally symmetric about the WNPAC associated with El Niño, rather than shifted westward as that in the observation”; “simulated La Niña events decay much faster than observed,” and “the precipitation anomalies over East Asia, especially those of the Meiyu rain belt, are much weaker than that in the observation.”

According to Chaudhari *et al.* (2013), “despite the potential for tropical climate predictability, and the advances made in the development of climate models, the seasonal dynamical forecast of [the] Indian summer monsoon remains a challenging problem,” which explored via a study of model biases and how they create further biases as they wend their way through multiple stages of both simultaneous and sequential processes. Chaudhari *et al.* examined the performance of the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) over the Indian monsoon region in a 100-year-long coupled run, framed “in terms of biases of sea surface temperature (SST), rainfall and circulation,” while also exploring “the role of

feedback processes in maintaining these biases.”

According to the nine researchers, the model shows dry (wet) rainfall bias concomitant with cold (warm) SST bias over the east (west) equatorial Indian Ocean. They say these biases of SST and rainfall affect both lower- and upper-level circulations in a feedback process, which in turn regulates the SST and rainfall biases by maintaining a coupled feedback process. Subsequently, a dry (wet) rainfall bias over the east (west) Indian Ocean induces anomalous low level easterlies over the tropical Indian Ocean and causes cold SST bias over the east Indian Ocean by triggering evaporation and warm SST bias over the west Indian Ocean through advection of warm waters. They find the persistent SST bias then retains the zonal asymmetric heating and meridional temperature gradient, resulting in a circum-global subtropical westerly jet core, which in turn magnifies the mid-latitude disturbances and decreases the Mascarene high, which in its turn diminishes the strength of monsoon cross-equatorial flow and results in less upwelling as compared to that in the observations. The latter phenomenon, they say, increases the SST bias over the West Indian Ocean. In conclusion, Chaudhari *et al.* state, “the coupled interaction among SST, rainfall and circulation works in tandem through a closed feedback loop to maintain the model biases over the tropical Indian Ocean.”

In one additional study on the Asian monsoon, Bollasina and Ming (2013) note most current general circulation models “show a remarkable positive precipitation bias over the southwestern equatorial Indian Ocean (SWEIO), which can be thought of as a westward expansion of the simulated IO convergence zone toward the coast of Africa.” They further note “the bias is common to both coupled and uncoupled models, suggesting that its origin does not stem from the way boundary conditions are specified.”

To further explore this issue, Bollasina and Ming “comprehensively characterized” “the spatio-temporal evolution of the precipitation and associated three-dimensional atmospheric circulation biases ... by comparing the GFDL [Geophysical Fluid Dynamics Laboratory] AM3 atmospheric model to observations.”

In the words of the two researchers, “the oceanic bias, which develops in spring and reduces during the monsoon season, is associated [with] a consistent precipitation and circulation anomalous pattern over the whole Indian region,” where “in the vertical, the areas are linked by an anomalous Hadley-type meridional circulation, whose northern branch

subsides over northeastern India significantly affecting the monsoon evolution (e.g., delaying its onset).” They find “the ability of local anomalies over the SWEIO to force a large-scale remote response to the north is further supported by numerical experiments with the GFDL spectral dry dynamical core model.”

Bollasina and Ming say their study “makes the case that the precipitation bias over the SWEIO is forced by the model excess response to the local meridional sea surface temperature gradient through enhanced near-surface meridional wind convergence.” They thus conclude “a detailed investigation into the model physics to identify possible parameters which may alleviate the model bias would be the natural extension of this work.”

Shifting to the African monsoon, writing as background for their work, authors Zheng and Braconnot (2013) report “despite recent progress in the monitoring and understanding of the WAM [West African Monsoon] within the framework of the African Monsoon Multidisciplinary Analysis (AMMA), there are still large uncertainties in projections of future climate in this region, such that even the sign of future precipitation change is uncertain,” citing Solomon *et al.* (2007). The authors “revisit the results of PMIP2 simulations over Africa using two approaches.” The first “considers the ensemble of simulations in order to determine how well the PMIP2 models [of today] reproduce some of the basic features of the summer monsoon precipitation,” while the objective of the second is “to understand model differences by considering model characteristics for present-day climate and their sensitivities to insolation change.”

The scientists learned several things from the simulations. First, they report, the “meridional temperature gradient is underestimated between 0° and 20°N by the PMIP2 model median, resulting in a smaller gradient of sea level pressure between the Gulf of Guinea and [the] Sahel,” which helps to explain “a lower than observed low-level moisture flux and an underestimate of rainfall intensity when compared with observations.” Second, “the northward extent of the rain belt and the intensity of precipitation change are underestimated.” Third, “the models overestimate the solar radiation.” Fourth, the models “underestimate the cloud radiative forcing in deep and moderate convective regimes.” And fifth, “some of the models have too strong a coupling between the latent heat and convection in deep convective regimes.”

Moving across the Atlantic to North America, according to Cerezo-Mota *et al.* (2011), “the North American monsoon (NAM) is the regional-scale atmospheric circulation system (Stensrud *et al.*, 1997) responsible for the dramatic increase in precipitation during the summer in northwestern Mexico and the southwest United States (Grantz *et al.*, 2007).” They state “understanding the mechanisms that govern the timing and intensity, as well as the impacts of climate change on the NAM, is a priority for the scientific community, watershed managers and farmers in the NAM area” because “the impacts of droughts/floods are devastating.”

Cerezo-Mota *et al.* investigated the degree of realism in its simulation by a major regional climate model (RCM)—the Hadley Centre Regional Model version 3P (HadRM3P)—analyzing the moisture sources of the NAM by employing two different boundary-condition data sets used to drive the model, which allowed them to assess the ability of the RCM to reproduce rainfall under climate-change conditions in the NAM region as predicted by GCMs.

As a result of their tests, the three U.K. researchers determined “two of the most commonly used GCMs that simulate well the NAM precipitation (HadCM3 and MIROC) do not reproduce correctly the Great Plains low-level jet nor the moisture in the Gulf of Mexico,” both of which play major roles in the northern portion of the NAM. The implication of their results, in the words of Cerezo-Mota *et al.*, is that “precipitation in Arizona-New Mexico would not be correctly represented by a regional model driven by these GCMs.” Thus, they write RCMs driven by the “most commonly used” GCMs “would not give realistic simulations of the current climate of the region and therefore would not offer a realistic projection of climate change of the NAM.”

Moving further south and using real-world data pertaining to the onset, end, and total rainfall of the South American Monsoon System (SAMS)—as characterized by precipitation data for the period 1979–2006, derived from the Global Precipitation Climatology Project—Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models with distinct physics and resolutions to simulate real-world SAMS characteristics. Over northern South America, they find the annual precipitation cycle “is poorly represented by most models” and “most models tend to underestimate precipitation during the peak of the rainy season.” In addition, they write, “the misrepresentation of the Intertropical Convergence Zone and its seasonal cycle

seems to be one of the main reasons for the unrealistic out-of-phase annual cycles simulated near the equator by many GCMs” and “poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models.” As a consequence, they note, “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 for most models.”

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1.4.5.3 Extreme Precipitation

Atmospheric general circulation models (GCMs) predict the planet’s hydrologic cycle will intensify as the world warms, leading to an increase in the frequency and intensity of extreme precipitation events. In an early review of the subject, Walsh and Pittock (1998) reported “there is some evidence from climate model studies that, in a warmer climate, rainfall events will be more intense” and “there is considerable evidence that the frequency of extreme rainfall events may increase in the tropics.” Upon further study, however, they concluded, “because of the insufficient resolution of climate models and their generally crude representation of sub-grid scale and convective processes, little confidence can be placed in any definite predictions of such effects.”

More than a decade later, Lim and Roderick (2009) compared the water cycle characteristics of the 39 model runs used in the IPCC AR4 (2007) assessment. The range of annual average global precipitation for the period 1970–1999 was 916.5 to 1,187.2 mm/yr. For the A1B scenario of CO₂ increase over the twenty-first century the increase in model precipitation ranged between 22.9 and 69.1 mm/yr with those that warmed the most generally showing greater increase in precipitation. The rate of increase in precipitation with temperature over the period, averaged about 2%/°C. A surprising result was the marked difference in the distribution of rainfall

increase: At one extreme most rainfall was over the land, and at the other it was mostly over the oceans; the other models fell across the range between the extremes.

A detailed analysis of how the models compared over Australia demonstrated even more variability. Lim and Roderick found the 1970–1999 annual rainfall of the models ranged from 190.6 mm to 1059.1 mm, whereas the observed rainfall is in the range between 400 and 500 mm. Across the twenty-first century under the A1B scenario, 24 models returned an increase in precipitation over Australia, while 15 showed decreases. Some models had the evaporation over Australia (and the Middle East) exceeding precipitation.

Stephens *et al.* (2010) write that in prior studies “land surface observations of the daily-accumulated rainfall intensities of rates >1 mm/day were compiled from the Global Historical Climatology Network by Sun *et al.* (2006) and compared to analogous model accumulated precipitation,” and they report “as in other studies (e.g., Dai and Trenberth, 2004), the Sun *et al.* comparison revealed a general overestimate in the frequency of modeled precipitation and an associated underestimate of intensity,” while noting “Wilcox and Donner (2007) reached a similar conclusion.” To further examine the issue Stephens *et al.* focused on the much larger portion of the planet that is occupied by oceans, using “new and definitive measures of precipitation frequency provided by CloudSat [e.g., Haynes *et al.*, 2009]” to assess the realism of global model precipitation. Their analysis employed five different computational techniques representing “state-of-the-art weather prediction models, state-of-the-art climate models, and the emerging high-resolution global cloud ‘resolving’ models.”

Stephens *et al.* determined “the character of liquid precipitation (defined as a combination of accumulation, frequency, and intensity) over the global oceans is significantly different from the character of liquid precipitation produced by global weather and climate models,” noting “the differences between observed and modeled precipitation are larger than can be explained by observational retrieval errors or by the inherent sampling differences between observations and models.” More specifically, they report for the oceans as a whole, “the mean model intensity lies between 1.3 and 1.9 times less than the averaged observations” and occurrences “are approximately twice the frequency of observations.” They also note the models “produce too much

precipitation over the tropical oceans” and “too little mid-latitude precipitation.” And they indicate the large model errors “are not merely a consequence of inadequate upscaling of observations but indicative of a systemic problem of models more generally.”

In concluding their study, the nine U.S., U.K., and Australian researchers say their results imply state-of-the-art weather and climate models have “little skill in precipitation calculated at individual grid points” and “applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system.”

In a study published in the *Journal of Climate*, Rossow *et al.* (2013) write “some of the concern about possible negative impacts of a warming climate is focused on possible increases of precipitation extremes.” They sought to “exploit more than a decade of independent cloud and precipitation data products covering the whole tropics (15°S–15°N) to more clearly separate the contributions to average precipitation intensity and daily average accumulation rate made by the different types of deep convective systems,” focusing on the period 1998–2008.

The four researchers determined “the whole distribution of instantaneous precipitation intensity and daily average accumulation rate is composed of (at least) two separate distributions representing distinctly different types of deep convection associated with different meteorological conditions.” In particular, they found the extreme portion of the tropical precipitation intensity distribution “is produced by 40% of the larger, longer-lived mesoscale-organized type of convection with only about 10% of the ordinary convection occurrences producing such intensities.” When accumulation rates were considered, they found “essentially all of the values above 2 mm/hour are produced by the mesoscale systems.”

Rossow *et al.* note “all of the climate GCMs currently parameterize tropical deep convection as a single process, localized to individual grid cells (on the order of 25–200 km in size) with short lifetimes (on the order of minutes to a few hours) that most resembles ordinary cumulonimbus.” Thus, “today’s atmospheric models do not represent mesoscale-organized deep convective systems that are generally larger than current-day circulation model grid cell sizes but smaller than the resolved dynamical scales.”

On the basis of these observations, the four researchers contend “the observed distinctive behavior of the different deep convective storm types

undercuts the simple projection of changes of extremes based on the large-scale balances or by a simple scaling.” And they say “these results draw attention to the need to understand why different deep convective storm types exist, how they interact with each other and with the larger-scale circulation, and what role they each play in the atmospheric general circulation.” With respect to the ultimate consequence of these model deficiencies, in the concluding sentence of their paper the four researchers state: “Until the full range of deep convective processes in the tropics is more realistically represented in climate models, they cannot be used to predict the changes of extreme precipitation events in a changing (warming) climate.”

Schleip *et al.* (2010) compared the results of six regional climate models (RCMs) that were forced with a common set of reanalysis data created by running a climate model fed real-world data for a 20-year simulation period. The area analyzed was North America, where winter precipitation was the response variable and the 100-year extremum of daily winter precipitation was the test statistic, extreme values of which were estimated by fitting a tailed distribution to the data, taking into account their spatial aspects.

The six RCMs maintained similar general spatial patterns of extrema across North America, with the highest extremes in the Southeast and along the West Coast. However, when comparing absolute levels, which are most relevant to risk forecasts, the models exhibited strong disagreement. The lowest-predicting model was low almost everywhere in North America compared to the mean of the six models, and the highest-predicting model was above the mean almost everywhere. The difference between the two models was almost 60mm of daily precipitation for the 100-year extreme event over much of the United States. The other four models showed greatly differing spatial patterns of extremes from each other, and these differences were found to be statistically significant by an F-test. The researchers speculate that when driven by multiple GCMs rather than reanalysis data, the range of extreme outcomes would only increase.

Other studies have further demonstrated the difficulties models have in simulating extreme precipitation properties and trends. Kiktev *et al.* (2007), for example, analyzed the abilities of five global coupled climate models that played important roles in the IPCC’s *Fourth Assessment Report* to simulate temporal trends over the second half of the twentieth century for five annual indices of

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precipitation extremes. Their results revealed “low skill” or an “absence” of model skill.

More of the same was reported by O’Gorman and Schneider (2009), who assessed “how precipitation extremes change in simulations with 11 different climate models in the World Climate Research Program’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) archive.” Based on their findings, as well as those of others, O’Gorman and Schneider report, “in simulations with comprehensive climate models, the rate of increase in precipitation extremes varies widely among models, especially in the tropics (Kharin *et al.*, 2007).” They also note, “the variations among models in the tropics indicate that simulated precipitation extremes may depend sensitively on the parameterization of unresolved and poorly understood processes,” citing the work of Wilcox and Donner (2007). They find, “climate models do not correctly reproduce the interannual variability of precipitation extremes in the tropics (Allan and Soden, 2008), or the frequency and intensity distribution of precipitation generally (Wilcox and Donner, 2007; Dai, 2006; Sun *et al.*, 2006).” Thus the two researchers conclude, “current climate models cannot reliably predict changes in tropical precipitation extremes,” noting “inaccurate simulation of the upward velocities may explain not only the intermodal scatter in changes in tropical precipitation extremes but also the inability of models to reproduce observed interannual variability.”

Noting “a number of articles in the media and reports by some non-governmental organizations have suggested an increasing number of heavy precipitation events over portions of the western United States and have proposed that anthropogenic global warming could be the cause,” Mass *et al.* (2011) analyzed “trends in heavy precipitation for the period 1950–2009 by examining the decadal distributions of the top 60, 40 and 20 two-day precipitation events for a collection of stations along the coastal zone of the United States and British Columbia [Canada], as well as the decadal distribution of maximum daily discharge for unregulated rivers from northern California to Washington State.”

The three researchers from the University of Washington’s Department of Atmospheric Sciences report their findings showed “during the past 60 years there has been a modest increase in heavy precipitation events over southern and central coastal California, a decline in heavy events from northern California through the central Oregon coast, a

substantial increase in major events over Washington, and a modest increase over coastal British Columbia.” However, they note, “most of these trends are not significantly different from zero at the 95% level.” In addition, they found “trends in maximum daily discharge of unregulated rivers are consistent with the above pattern, with increasing discharges over the past three decades over Washington and northern Oregon and declines over the remainder of Oregon and northern California.”

With respect to how consistent these results are with what climate models suggest should occur in response to rising temperatures, Mass *et al.* report the results of the two climate models analyzed by Chen *et al.* (2003) suggest “a pattern quite different from the one described above,” and they state the model employed by Kim (2005) also produced “a pattern quite distinct from that observed since 1950.” In addition, they note the models studied by Tebaldi *et al.* (2006) produced “a pattern closer, but not identical to, that observed over the past 60 years,” and Duffy *et al.* (2006) “analyzed the precipitation produced over the western United States by four regional climate models,” finding the spatial distributions of precipitation they produced to “vary substantially,” even among themselves.

Mass *et al.* conclude, “considering the large variability in precipitation trends among the various general circulation models in the above studies and their associated regional climate models, and the differences between the simulated trend distributions and the observed trend patterns found in this study and others, it is unclear whether anthropogenic global warming is the source of past spatial patterns of extreme precipitation trends along the west coast of North America.”

Mishra *et al.* (2012) point out “about half of the human population lives in urban areas (Martine *et al.*, 2007), in contrast with only about 10 percent a century ago (Grimm *et al.*, 2008).” Therefore, they note, “changes in extreme precipitation as the climate warms may pose challenges for stormwater management in urban areas, because most stormwater infrastructure was designed under the assumption of stationary climate that is ‘dead’ as argued by Milly *et al.* (2008).”

In an effort to better assess both the likelihood and significance of this potential problem, Mishra *et al.* compared precipitation output from all regional climate models that participated in the North American Regional Climate Change Assessment Program (NARCCAP), described by Mearns *et al.*

(2009), with observations made at 100 urban U.S. weather stations with data for the period 1950–2009. This work involved two distinct RCM simulations: one forced by output from the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis (Kanamitsu *et al.*, 2002) for the period 1979–2000, and one forced by selected global circulation models that provided RCM boundary conditions for the period 1968–2000.

The analysis showed, “for most urban areas in the western and southeastern U.S.,” in the words of the three scientists, “the seasonality of 3-hour precipitation extremes was not successfully reproduced by the RCMs with either reanalysis or GCM boundary conditions,” because “the RCMs tended to predict 3-hour precipitation maxima in winter, whereas the observations indicated summer.” The authors also report the RCMs “largely underestimated 3-hour precipitation maxima means and 100-year return period magnitudes at most locations across the United States for both reanalysis and GCM boundary conditions.” For both 3- and 24-hour annual precipitation maxima, they write, “RCMs with reanalysis boundary conditions underestimated interannual variability” while they “overestimated interannual variability with GCM boundary conditions.”

With respect to the ultimate utility of the RCM projections, Mishra *et al.* state performance deemed acceptable for stormwater infrastructure design was adequate at only about 25 percent of the urban areas. Regardless of boundary conditions, they note, “RCM-simulated 3-hour precipitation maxima at a 100-year return period could be considered acceptable for stormwater infrastructure design at less than 12% of the 100 urban areas.”

Khoi and Suetsugi (2012) write “many general circulation models (GCMs) consistently predict increases in frequency and magnitudes of extreme climate events and variability of precipitation (IPCC, 2007),” noting “this will affect terrestrial water resources in the future, perhaps severely (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Chen *et al.*, 2011).” Therefore, they conducted a study to see what aspect of the climate modeling enterprise led to the greatest degree of uncertainty in predicting rates of streamflow in Vietnam’s Be River Catchment. The climate scenarios investigated by Khoi and Suetsugi were generated from seven different CMIP3 GCMs—CCCMA CGCM3.1, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM3.0, UKMO HadGEM1, UKMO Had CM3—using SRES emission scenarios

A1B, A2, B1, and B2, along with prescribed increases in global mean temperature ranging from 0.5 to 6°C.

The two Vietnamese researchers report finding “the greatest source of uncertainty in impact of climate change on streamflow is GCM structure (choice of GCM).” They say this result “is in accordance with findings of other authors who also suggest that the choice of the GCM is the largest source of uncertainty in hydrological projection,” citing Kingston and Taylor (2010), Kingston *et al.* (2011), Nobrega *et al.* (2011), Thorne (2011), and Xu *et al.* (2011), adding the range of uncertainty could increase even further if the analysis employed a larger number of GCMs.

Khoi and Suetsugi say their findings indicate “single GCM or GCMs ensemble mean evaluations of climate change impact are unlikely to provide a representative depiction of possible future changes in streamflow.”

In one other streamflow-based study, Lloyd (2010) notes the Breede River “is the largest in South Africa’s Western Province, and plays a significant part in the province’s economy,” and “models predict that flows into it could be seriously affected by climate change.” More specifically, he reports Steynor *et al.* (2009) used “a form of neural network” “trained on historical climate data” that were “linked to historical flow data at five stations in the Breede River valley” in order to “downscale from a global climate model to the typical area of a catchment” and thereby determine the consequences of predicted future global warming for Breede River flows. That analysis projected Breede River flows would decrease if temperatures rise as predicted by climate models over the next 60 years.

As a check upon this approach to projecting the region’s hydrologic future, Lloyd, a researcher at the Energy Institute of the Cape Peninsula University of Technology located in Cape Town, used flow data for five sites in the Breede Valley that had been maintained by the Department of Water Affairs to compute historical flow-rate trends over prior periods of warming ranging from 29 to 43 years in length.

All of the future flow-rates calculated by Steynor *et al.* exhibited double-digit negative percentage changes that averaged -25% for one global climate model and -50% for another global climate model. Similarly, the mean past trend of four of Lloyd’s five stations was also negative (-13%). But the other station exhibited a positive trend (+14.6%). In addition, by “examination of river flows over the past 43 years in the Breede River basin,” Lloyd was able

to demonstrate that “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.

Interestingly, Steynor *et al.* had presumed warming would lead to *decreased* flow rates, as their projections suggested, and they thus 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, and that in his newer study the one site with “a pristine watershed” was the one that had the “14% increase in flow over the study period,” which was “contrary to the climate change predictions” and indicative of the fact that “climate change models cannot yet account for local climate change effects.” Lloyd concludes “predictions of possible adverse local impacts from global climate change should therefore be treated with the greatest caution” and, “above all, they must not form the basis for any policy decisions until such time as they can reproduce known climatic effects satisfactorily.”

Van Haren *et al.* (2013) write “estimates of future changes in extremes of multi-day precipitation sums are critical for estimates of future discharge extremes of large river basins and changes in [the] frequency of major flooding events,” citing Kew *et al.* (2010). They indicate “a correct representation of past changes is an important condition to have confidence in projections for the future.”

In an attempt to achieve some of that all-important confidence, van Haren *et al.* investigated changes in multi-day precipitation extremes in late winter in Europe and the Rhine river basin over the past 60 years using daily precipitation data and “the state-of-the-art gridded high resolution (0.5°) precipitation fields of the European ENSEMBLES project version 7.0 (Haylock *et al.* 2008),” where “observations [were] averaged to the same regular 1.5° grid when compared directly with the model results.”

The four researchers report the climate models “underestimate the trend in extreme precipitation in the northern half of Europe” because they “underestimate the change in circulation over the past century and as a result have a much smaller (extreme) precipitation response.” More specifically, they state “a dipole in the sea-level pressure trend over continental Europe causes positive trends in extremes in northern Europe and negative trends in the Iberian Peninsula,” while “climate models have a much weaker pressure trend dipole and as a result a much

weaker (extreme) precipitation response.”

Van Haren *et al.* conclude their report by declaring “it is important that we improve our understanding of circulation changes, in particular related to the cause of the apparent mismatch between observed and modeled circulation trends over the past century,” citing Haarsma *et al.* (2013).

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1.3.6 Temperature

How much of the warming of the past 100 years is due to human activity? When multiple forcings are varying and poorly characterized, and there is also internal variation, this question is more difficult, if not impossible, to answer. Nevertheless, several studies have attempted to do so

1.3.6.1 Surface and Near-Surface

Citing the work of Folland *et al.* (2001), Robinson *et al.* (2002), and Pan *et al.* (2004), Kunkel *et al.* (2006) note there was a lack of warming throughout the central and southeastern United States over the course of the twentieth century, dubbed a “warming hole” by the latter set of investigators. For an area they denote the Central United States (CUS), which they described as “one of the most agriculturally productive regions of the world and roughly defined around what is known as the ‘Corn Belt,’” Kunkel *et al.* used a data set of 252 surface climate stations with less than 10 percent missing temperature data over the period 1901–1999 to construct the CUS temperature time series plotted in Figure 1.3.6.1.1, where mean global temperature as determined by Hansen *et al.* (2001) is also plotted. Then, for comparative purposes, they examined 55 coupled general circulation model (CGCM) simulations driven by “modern estimates of time-varying forcing” plus 19 preindustrial unforced simulations, all derived from 18 CGCMs.

It is obvious, as shown in Figure 1.3.6.1.1, that the Central U.S. twentieth century temperature series is vastly different from that of the globe as a whole, at least as the latter is represented by Hansen *et al.* Rather than the final temperature of the twentieth century being warmer than the rest of the century, for this region it was more than 0.7°C cooler than it was a mere 65 years earlier. In addition, Kunkel *et al.* report

“the warming hole is not a robust response of contemporary CGCMs to the estimated external forcings.”

Kiktev *et al.* (2007) introduce their study by stating the importance of “comparing climate modeling results with historical observations ... to further develop climate models and to understand the capabilities and limitations of climate change projections.” They analyzed the abilities of five global coupled climate models that played important roles in the IPCC’s *Fourth Assessment Report* to simulate temporal trends over the second half of the twentieth century of five annual indices of extremes in surface temperature—annual percentage of days with $T_{\min} < 10\text{th percentile}$, with $T_{\max} < 10\text{th percentile}$, with $T_{\min} > 90\text{th percentile}$, with $T_{\max} > 90\text{th percentile}$, and annual number of frost days, i.e., $T_{\min} < 0^{\circ}\text{C}$ —as well as five annual indices of extremes in precipitation, the observational data for which they obtained from the HadEX global data set that contains gridded annual and seasonal values of the ten extreme indices calculated from series of *in situ* daily measurements (Alexander *et al.*, 2006). The international research team, hailing from Australia, Japan, Russia, and the United Kingdom, state “the results mostly show moderate skill for temperature indices.”

In an effort “to distinguish between simultaneous natural and anthropogenic impacts on surface temperature, regionally as well as globally,” Lean and Rind (2008) performed “a robust multivariate analysis using the best available estimates of each together with the observed surface temperature record from 1889 to 2006.” They report, “contrary to recent assessments based on theoretical models (IPCC, 2007) the anthropogenic warming estimated directly from the historical observations is more pronounced between 45°S and 50°N than at higher latitudes,” which, in their words, “is the approximate inverse of the model-simulated anthropogenic plus natural temperature trends ... which have minimum values in the tropics and increase steadily from 30 to 70°N.” Furthermore, they continue, “the empirically-derived zonal mean anthropogenic changes have approximate hemispheric symmetry whereas the mid-to-high latitude modeled changes are larger in the Northern hemisphere.” The two researchers conclude “climate models may therefore lack—or incorrectly parameterize—fundamental processes by which surface temperatures respond to radiative forcings.”

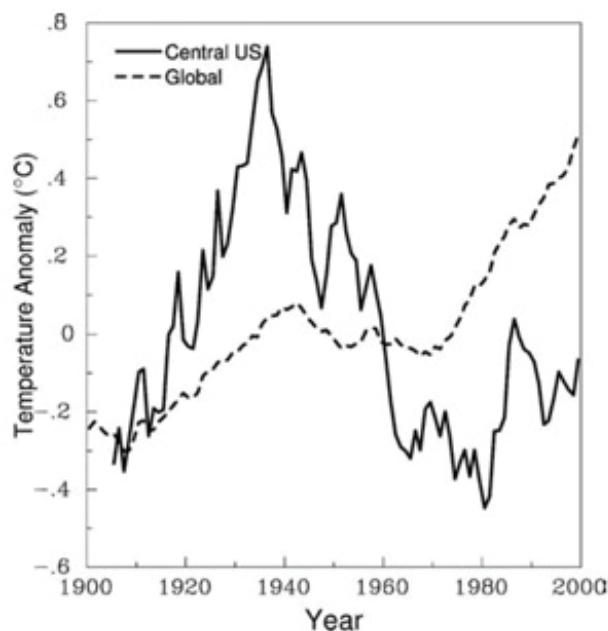


Figure 1.3.6.1.1. Twentieth-century Central United States and mean global temperature anomalies. Reprinted with permission from Kunkel, K.E., Liang, X.-Z., Zhu, J., and Lin, Y. 2006. Can CGCMs simulate the twentieth-century “warming hole” in the central United States? *Journal of Climate* 19: 4137–4153.

Chylek *et al.* (2009) point out “one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback.” More specifically, they say, “the surface air temperature change in the Arctic is predicted to be about two to three times the global mean,” citing the IPCC (2007). In conducting their own study, the authors utilized Arctic surface air temperature data from 37 meteorological stations north of 64°N in an effort to explore the latitudinal variability in Arctic temperatures within two belts—the low Arctic (64°N–70°N) and the high Arctic (70°N–90°N)—comparing them with mean global air temperatures over three sequential periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

The five researchers report, “the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean.” More precisely, the Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that is the end of the real world’s climate-change agreement with theory. During the 1910–1940

warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic. Such findings constitute another important example of the principle described by Reifen and Toumi (2009): that a model that performs well for one time period will not necessarily perform well for another.

Expounding on this principle, Reifen and Toumi (2009) note, “with the ever increasing number of models, the question arises of how to make a best estimate prediction of future temperature change.” That is to say, which model should one use? With respect to this question, they note, “one key assumption, on which the principle of performance-based selection rests, is that a model which performs better in one time period will continue to perform better in the future.” In other words, if a model predicts past climate fairly well, it should predict future climate fairly well. The principle sounds reasonable enough, but does it hold true?

Reifen and Toumi examined this question “in an observational context” for what they describe as “the first time.” Working with the 17 climate models employed by the IPCC in its *Fourth Assessment Report*, they determined how accurately individual models, as well as subsets of the 17 models, simulated the temperature history of Europe, Siberia, and the entire globe over a selection period (such as 1900–1919) and a subsequent test period (such as 1920–1939), asking whether the results for the test period are as good as those of the selection period. They followed this procedure while working their way through the entire twentieth century at one-year time-steps for not only 20-year selection and test intervals but also for 10- and 30-year intervals.

The two researchers could find “no evidence of future prediction skill delivered by past performance-based model selection,” noting, “there seems to be little persistence in relative model skill.” They speculate “the cause of this behavior is the non-stationarity of climate feedback strengths,” which they explain by stating, “models that respond accurately in one period are likely to have the correct feedback strength at that time,” but “the feedback strength and forcing is not stationary, favoring no particular model or groups of models consistently.” Given such findings, the U.K. physicists conclude their analysis of the subject by stating “the common

investment advice that ‘past performance is no guarantee of future returns’ and to ‘own a portfolio’ appears also to be relevant to climate projections.”

Also studying the Arctic, Liu *et al.* (2008) “assessed how well the current day state-of-the-art reanalyses and CGCMs [coupled global climate models] are reproducing the annual mean, seasonal cycle, variability and trend of the observed SAT [surface air temperature] over the Arctic Ocean for the late twentieth century (where sea ice changes are largest).” The results indicate “large uncertainties are still found in simulating the climate of the twentieth century,” they write, and on an annual basis, “almost two thirds of the IPCC AR4 models have biases that [are] greater than the standard deviation of the observed SAT variability.” Liu *et al.* further note the models “cannot capture the observed dominant SAT mode variability in winter and seasonality of SAT trends.” The majority of the models “show an out-of-phase relationship between the sea ice area and SAT biases,” they write, and “there is no obvious improvement since the IPCC *Third Assessment Report*.”

Anagnostopoulos *et al.* (2010) evaluate the ability of models used by the IPCC to generate regional climates to reproduce observed climate and climate change, and they take issue with the IPCC’s assessment of its models. They compare the output of these models to temperature and precipitation observations at 55 points worldwide. They then do a similar comparison for 70 points in the USA on several time scales. They selected the USA for the refined study because it has a dense network of surface stations. Thus, they can evaluate the model performance at the large scale and the regional scale.

In order to compare observed records to model projections, they use a statistical technique called “best linear unbiased estimation,” comparing observations at a particular station and nearby stations to a linear combination of the model outputs and comparing the time series via traditional statistical measures.

The authors demonstrate, “At the monthly time scale the models generally reproduce the sequence of cold-warm and wet-dry periods at all stations examined.” However, the results were much worse at the annual time scale and the variability in the general circulation is underestimated. For the climate time-scales, some of the grid points will show 30-year temperature rises in the model simulation, but the actual data shows temperature falls. This is similar for both the large and regional scales. Additionally, the

models could not capture the long-term climate changes from 1890 to the end of the twentieth century at many of the points (Figure 1.3.6.1.2).

As Anagnostopoulos *et al.* state, “It is claimed that GCMs provide credible quantitative estimates of future climate change, particularly at continental times scales and above. Examining the local performance of the models at 55 points, we found that local projections do not correlate well with observed measurements.” They found the model performance was actually worse on larger scales than on regional ones. They suggest the central issue is not about the performance of the GCMs, but whether climate can be predicted deterministically at all given the uncertainties inherent in the atmosphere.

Anagnostopoulos *et al.* use statistics to make the point others have made regarding models using dynamics. Anagnostopoulos *et al.* say there simply may not be a predictable “core” to the climate that is only obscured by layers of complexity or uncertainty. They also propose a shift in our modeling approach, suggesting statistical methods, in addition to dynamical methods and models, be used to generate future scenarios for climate as has been done successfully in other fields such as thermophysics or turbulence.

Lo and Hsu (2010) point out “widespread abrupt warming in the extratropical Northern Hemisphere occurred in the late 1980s” and say the warming was associated with a change in the relative influence of a Pacific Decadal Oscillation (PDO)-like pattern and an Arctic Oscillation (AO)-like pattern. Utilizing land surface temperature data obtained from the University of East Anglia’s Climatic Research Unit (Mitchell *et al.*, 2004), plus sea surface temperature data obtained from the U.K.’s Meteorological Office (Rayner *et al.*, 2003), the authors explored the nature of this temperature increase and tested the ability of IPCC/CMIP3 models to simulate it.

The two Taiwanese researchers report the “accelerated warming in the Northern Hemisphere” was related to the emergence of an AO-like pattern in the late 1980s and the concomitant weakening of the previously prevailing PDO-like pattern occurring in tandem. These results they say, , together with results obtained from current IPCC/CMIP3 models, “do not support the scenario that the emerging influence of the AO-like pattern in the 1980s can be attributed to the anthropogenic greenhouse effect.” Lo and Hsu also conclude, “this study indicates the importance of the changing behavior of the decadal fluctuations in the recent climate regime shift,” and they highlight

Climate Change Reconsidered II

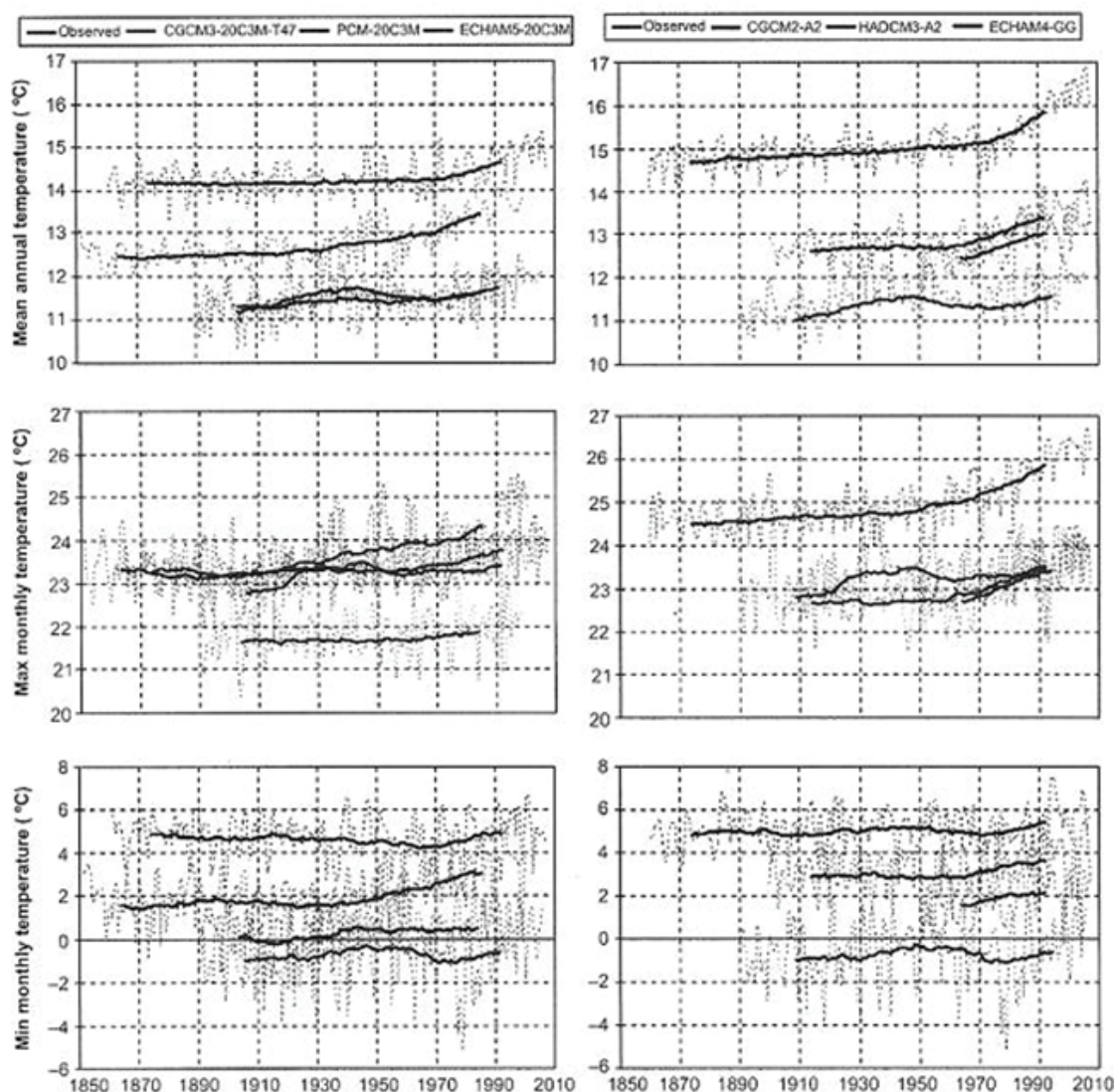


Figure 1.3.6.1.2. The observed and model temperature time series integrated over the USA (annual means and maximum and minimum monthly) for the annual and 30-year time scales. Adapted from Anagnostopoulos, G.G., Koutsoyiannis, D., Christofides, A., Efstradiadis, A., and Mamassis, N. 2010. A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal* 55: 1094–1110, Figure 12.

what they call “the insufficient capability of the present state-of-the-art IPCC/CMIP3 models in simulating this change.”

DeSole *et al.* (2011) used a set of climate models run in “control” or unforced mode to develop a 300-year data set of spatial ocean temperature data, where it was found that an internal pattern, detectable using a spatial fingerprinting technique, could be identified in the simulated data. This spatial pattern of ocean temperature anomalies was labeled the Internal Multidecadal Pattern (IMP). It was found to be highly coherent with the Atlantic Multidecadal Oscillation

(AMO), suggesting the models were able to match the internal dynamics of the real-Earth system reasonably well. The researchers next extracted, also by means of discriminant fingerprinting, the forced component of the spatial patterns produced in the absence of the IMP as an orthogonal function, which they demonstrated has only a minor effect (less than 1/7 the amplitude) on the IMP. They then used historical sea surface temperature data to evaluate the relative importance of the forced vs. IMP components of change since 1850.

In considering the latter portion of the record

(1946–2008), the results indicate the internal variability component of climate change (the IMP) operated in a cooling mode between 1946 and 1977, but switched thereafter to a warming mode between 1977 and 2008, suggesting the IMP is strong enough to overwhelm any anthropogenic signal during this latter period of time. They also note “the trend due to only the forced component is statistically the same in the two 32-year periods and in the 63-year period.” That is to say, the forced part was not accelerating. Taken together, these results imply the observed trend differs between the periods 1946–1977 and 1977–2008 not because the forced response accelerated but because “internal variability led to relative cooling in the earlier period and relative warming in the later period.” Their results suggest simple extrapolations of rates of warming from 1980 onward overestimate the forced component of warming, and therefore using this period without factoring out internal variability will likely lead to unrealistic values of climate sensitivity.

Lavers *et al.* (2009), in a study described previously in Section 1.4.5.1, assessed the predictability of monthly “retrospective forecasts,” or hindcasts, composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001, comparing the projections against real-world air temperatures obtained from ERA-40 reanalysis data. In addition, they conducted a virtual-world analysis where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

The researchers report that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but there was a large drop-off in predictive skill in the second 15-day period. Things were worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, “a relatively short lead time in terms of seasonal climate prediction.” The three researchers conclude, “it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers,” a quest they state “may prove to be elusive.”

Crook and Forster (2011) note “predicting our future influence on climate requires us to have confidence in the climate models used to make predictions, and in particular that the models’ climate sensitivity and ocean heat storage characteristics are

realistic.” They go on to say that confidence may be gained “by assessing how well climate models reproduce current climatology and climate variability, and how their feedback parameters compare with estimates from observations.”

Using the World Climate Research Programme’s Coupled Model Intercomparison Project phase 3 (CMIP3) and real-world data from the HadCRUT3 database, Crook and Forster first determined “the surface temperature response contributions due to long-term radiative feedbacks, atmosphere-adjusted forcing, and heat storage and transport for a number of coupled ocean-atmosphere climate models,” after which they compared “the linear trends of global mean, Arctic mean and tropical mean surface temperature responses of these models with observations over several time periods.” They also investigated “why models do or do not reproduce the observed temperature response patterns” and performed “optimal fingerprinting analyses on the components of surface temperature response to test their forcing, feedback and heat storage responses.”

The two University of Leeds (U.K.) researchers found tropical twentieth century warming was too large and Arctic amplification too low in the Geophysical Fluid Dynamics Laboratory CM2.1 model, the Meteorological Research Institute CGCM232a model, and the MIROC3(hires) model “because of unrealistic forcing distributions.” They also determined “the Arctic amplification in both National Center for Atmospheric Research models is unrealistically high because of high feedback contributions in the Arctic compared to the tropics.” In addition, they report, “few models reproduce the strong observed warming trend from 1918 to 1940,” noting “the simulated trend is too low, particularly in the tropics, even allowing for internal variability, suggesting there is too little positive forcing or too much negative forcing in the models at this time.”

According to Miao *et al.* (2012), the accuracy of any GCM “should be established through validation studies before using it to predict future climate scenarios.” “Although accurate simulation of the present climate does not guarantee that forecasts of future climate will be reliable,” they write, “it is generally accepted that the agreement of model predictions with present observations is a necessary prerequisite in order to have confidence in the quality of a model.”

Working within this conceptual framework, Miao *et al.* assessed the performance of the AR4 GCMs, otherwise known as the CMIP3 models, in simulating

precipitation and temperature in China from 1960 to 1999, comparing the model simulations with observed data using “system bias (*B*), root-mean-square error (*RMSE*), Pearson correlation coefficient (*R*) and Nash-Sutcliffe model efficiency (*E*)” as evaluation metrics.

The four researchers find certain of the CMIP3 models “are unsuitable for application to China, with little capacity to simulate the spatial variations in climate across the country,” adding that all of them “give unsatisfactory simulations of the inter-annual temporal variability.” In addition, they find “each AR4 GCM performs differently in different regions of China.” Miao *et al.* conclude “the inter-annual simulations (temperature and precipitation) by AR4 GCMs are not suitable for direct application” and “caution should be applied when using outputs from the AR4 GCMs in hydrological and ecological assessments” due to their “poor performance.”

According to Morak *et al.* (2013), studies of observational temperature records over the past 50 to 100 years have found evidence for increases in both mean and extreme (maximum and minimum) near-surface air temperatures, but they note the increase in maximum temperature has been of smaller magnitude than the increase in minimum temperature. This state of affairs has led to a decrease in the diurnal temperature range. They compared “observed and climate model-simulated trends in mean values of temperature extreme indices, splitting the year into the dynamically active boreal cold (ONDJFM) and warm (AMJJAS) seasons.” To do so, they used “modeled daily minimum and maximum surface temperature data derived from simulations with the Hadley Centre Global Environmental Model, version 1 (HadGEM1).”

The three U.K. researchers report, among other findings, that the model “significantly underestimates changes in some regions, particularly in winter across large parts of Asia” and “has a tendency to overestimate changes in the frequency of hot days in both the [a] winter and [b] summer seasons over [d] most regions, and in the [e] global and [f] hemispheric mean.” The model “also overestimates changes in the frequency of warm winter days on larger scales.” With respect to changes in cold extremes the model “does underestimate them in some regions” and “there are some regions with trends of the opposite sign.” In addition, Morak *et al.* “the particular regional trend pattern, often also referred to as the ‘warming hole,’ is not evident in the simulated trend pattern,” citing Pan *et al.* (2004),

Kunkel *et al.* (2006), Portmann *et al.* (2009), and Meehl *et al.* (2012). And they say “the model shows a tendency to significantly overestimate changes in warm daytime extremes, particularly in summer.” Although the HadGEM1 does some things well, there are a number of other things it has yet to accomplish satisfactorily.

As the observed rate of rise in the global average temperature has slowed during recent decades, the gap between observations and climate models results has widened. The discrepancy is now so large as to indicate a statistically significant difference between the climate modeled trends and the observed trend. The existence of such a large discrepancy is a strong indication that climate models are failing in their ability to accurately capture known changes in this key parameter of Earth’s climate system.

A clear demonstration the models are failing to contain observations was made by Knappenberger and Michaels (2013), who compiled the range of trends in surface temperatures during the first several decades of the twenty-first century projected by CMIP3 climate models running emissions scenario A1B. Knappenberger and Michaels placed the observed temperatures within this modeled distribution (see Figure 1.3.6.1.3). The observed trends lie very close to, and in some cases below, the lower bound of the 95% certainty range derived from climate model projections. Knappenberger and Michaels report “at the global scale, climate models are on the verge of failing to adequately capture observed changes in the average temperature over the past 10 to 30 years—the period of the greatest human influence on the atmosphere.” They conclude, “It is impossible to present reliable future projections from a collection of climate models which generally cannot simulate observed change.”

In the same vein, Fyfe *et al.* (2013) examined the performance of the newer CMIP5 climate models and found a similar result. The researchers “considered trends in global mean surface temperature computed from 117 simulations of the climate by 37 CMIP5 models.” They note the “models generally simulate natural variability—including that associated with the El Niño–Southern Oscillation and explosive volcanic eruptions—as well as estimate the combined response of climate to changes in greenhouse gas concentrations, aerosol abundance (of sulphate, black carbon and organic carbon, for example), ozone concentrations (tropospheric and stratospheric), land use (for example, deforestation) and solar variability.” But despite the models’ claimed ability to simulate

Surface Air Temperature Trends

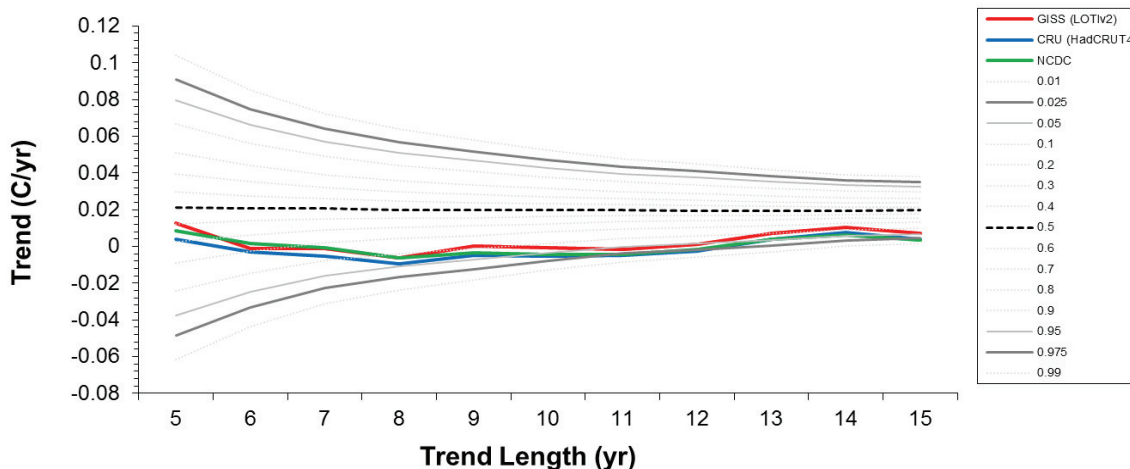


Figure 1.3.6.1.3. Trends (through 2012) in three observed global surface temperature records of length 5 to 15 years (colored lines) set against the probability (gray lines) derived from the complete collection of climate model runs used in the IPCC Fourth Assessment Report under the SRES A1B emissions scenario. Reprinted with permission from Knappenberger, P.C. and Michaels, P.J., 2013. Policy implications of climate models on the verge of failure. American Geophysical Union Science Policy Conference. Washington, DC, June 24–26, 2013.

both natural variability and human influences, when compared against actual observations, their simulation of the evolution of the global average temperature is flawed. Over the past 20 years (1993–2012), Fyfe *et al.* find the “rate of warming is significantly slower than that simulated by the climate models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5)” and “the inconsistency between observed and simulated global warming is even more striking for temperature trends computed over the past fifteen years (1998–2012).” They add, “It is worth noting that the observed trend over this period—not significantly different from zero—suggests a temporary ‘hiatus’ in global warming.” Fyfe *et al.* conclude, “Ultimately the causes of this inconsistency will only be understood after careful comparison of simulated internal climate variability and climate model forcings with observations from the past two decades, and by waiting to see how global temperature responds over the coming decades.”

The IPCC is in a very difficult position. In order to defend the CMIP5 suite of models, it must somehow argue they did *not* underpredict warming as the greatest increases in atmospheric carbon dioxide content occurred. Further, they must invalidate at least 19 separate experiments authored by 42 researchers in the citations noted earlier in this section.

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1.4.6.2 Mid- and Upper-Troposphere

Several studies have examined model treatment of processes in the troposphere. The testing of climate model results is an important but difficult problem. One of the key model results is the presence of a tropical troposphere “hotspot” in which the troposphere warms faster than the surface under conditions of enhanced greenhouse gas forcing. Previous studies have produced disagreement over whether data were consistent with models on this question. However, Christy *et al.* (2010) made several advances by enhancing the data for surface trends, extending the data to a 31-year length, evaluating the wind-based temperature estimates, and clarifying the meaning of “best estimate” multi-data warming trends from data and models.

Two prior studies had derived tropospheric temperature trends from the Thermal Wind Equation (TWE)—which uses radiosonde measurements of wind speed to calculate temperature—on the theoretical basis that warmer air should move faster

than cooler air. They found there were biases in the data for this type of calculation. For example, particularly for older radiosonde observations, on days when the upper wind was stronger, the balloons would tend to blow out of receiver range. This created a bias by causing missing data for high winds for older observations, leading to a spurious warm trend over time. Overall, the TWE-based trends were three times greater than trends derived from all other types of data. In addition, they did not agree with other wind data and also were based on much sparser data. Radiosonde data were therefore not used in the Christy *et al.* analysis, which also identified a small warm bias in the Remote Sensing System (RSS) satellite data that was explained by Christy and his colleagues.

The next innovation was to use the Scaling Ratio (SR), the ratio of atmospheric temperature trend to surface temperature trend. The SR attempts to factor out the effect of the lack of actual (historic) El Niños or other oscillations in climate model runs, and such simulated events in different computer runs. Christy and his eight colleagues found the SR for real-world data was 0.8 ± 0.3 , whereas the model simulations had a SR of 1.38 ± 0.08 (a significant difference). That is, the data show a lower rate of warming for the lower troposphere than for the surface (though not statistically different), whereas the models show amplification. The SR value for the middle troposphere data was 0.4, even more different from the model predictions. Only the SR for RSS data, which has a documented warming bias, overlaps with any model SR results. Given these findings, the work of Christy *et al.* suggests current state-of-the-art climate models are fundamentally wrong in how they represent this portion of Earth's atmosphere.

The tropical troposphere also was the focus of study for Fu *et al.* (2011), who note the IPCC *Fourth Assessment Report* (AR4) general circulation models “predict a tropical tropospheric warming that increases with height, reaches its maximum at ~200 hPa, and decreases to zero near the tropical tropopause.” They add, “this feature has important implications to the climate sensitivity because of its impact on water vapor, lapse rate and cloud feedbacks and to the change of atmospheric circulations.” Therefore, they write, it is “critically important to observationally test the GCM-simulated maximum warming in the tropical upper troposphere.”

Fu *et al.* thus examined trends in the temperature difference (ΔT) between the tropical upper- and lower-middle-troposphere based on satellite

microwave sounding unit (MSU) data, as interpreted by University of Alabama at Huntsville (UAH) and RSS teams, comparing both sets of results with AR4 GCM ΔT simulations for the period 1979–2010.

The three researchers report the RSS and UAH ΔT time series “agree well with each other” and showed little trend over the period of record. By contrast, they note there is “a steady positive trend” in the model-simulated ΔT results, concluding the significantly smaller ΔT trends from both the RSS and UAH teams “indicate possible common errors among AR4 GCMs.” In addition, they note the tropical surface temperature trend of the multi-model ensemble mean is more than 60% larger than that derived from observations, “indicating that AR4 GCMs overestimate the warming in the tropics for 1979–2010.”

In addition to greatly overestimating the tropical surface temperature trend, Fu *et al.* note, “it is evident that the AR4 GCMs exaggerate the increase in static stability between [the] tropical middle and upper troposphere during the last three decades.”

One year later, Po-Chedley and Fu (2012) write, “recent studies of temperature trend amplification in the tropical upper troposphere relative to the lower-middle troposphere found that coupled atmosphere-ocean models from CMIP3 exaggerated this amplification compared to satellite microwave sounding unit (Fu *et al.*, 2011) and radiosonde (Seidel *et al.*, 2012) observations.” The two authors “revisit this issue using atmospheric GCMs with prescribed historical sea surface temperatures (SSTs) and coupled atmosphere-ocean GCMs that participated in the latest model intercomparison project, CMIP5.”

The pair of researchers report their work demonstrated “even with historical SSTs as a boundary condition, most atmospheric models exhibit excessive tropical upper tropospheric warming relative to the lower-middle troposphere as compared with satellite-borne microwave sounding unit measurements.” In addition, they note, “the results from CMIP5 coupled atmosphere-ocean GCMs are similar to findings from CMIP3 coupled GCMs.”

Focusing more on the mid-troposphere, Handorf *et al.* (2012) write, “atmospheric teleconnections describe important aspects of the low-frequency atmospheric variability on time-scales of months and longer,” adding “in light of the increased need to provide reliable statements about seasonal to decadal predictability, it is necessary that state-of-the-art climate models simulate the spatial and temporal behavior of atmospheric teleconnections

satisfactorily.” Therefore, they continue, “an evaluation of climate models requires the evaluation of the simulated climate variability in terms of teleconnection patterns.” Handorf and Dethloff evaluated “the ability of state-of-the-art climate models to reproduce the low-frequency variability of the mid-tropospheric winter flow of the Northern Hemisphere in terms of atmospheric teleconnection patterns.” To do so, they used the CMIP3 multimodel ensemble for the period 1958–1999, for which reliable reanalysis data were available for comparison.

The two researchers conclude, “current state-of-the-art climate models are not able to reproduce the temporal behavior, in particular the exact phasing of the dominant patterns due to internally generated model variability.” In addition, they write, “the state-of-the-art climate models are not able to capture the observed frequency behavior and characteristic time scales for the coupled runs satisfactorily ... in accordance with Stoner *et al.* (2009) and Casado and Pastor (2012),” both of which studies conclude, in their words, that “the models are not able to reproduce the temporal characteristics of atmospheric teleconnection time-series.”

“In light of the strong need to provide reliable assessments of decadal predictability,” Handorf and Dethloff additionally state “the potential of atmospheric teleconnections for decadal predictability needs further investigations” that “require a better understanding of [1] the underlying mechanisms of variability patterns and flow regimes, [2] an improvement of the skill of state-of-the-art climate and Earth system models in reproducing atmospheric teleconnections and [3] the identification of sources for long-range predictive skill of teleconnections.”

In other research, Santer *et al.* (2011) examined the consistency between satellite observations of the lower troposphere and climate model simulations of that atmospheric region. The 17 researchers set the average of the observed temperature trends of lengths varying from 10 to 32 years against the distribution of the same trend as simulated by a collection of CMIP3 climate models (see Figure 1.4.6.2.1). While the lower troposphere temperature trends (TLT) “in the observational satellite datasets are not statistically unusual relative to model-based distributions of externally forced TLT trends” they found “it should be qualified by noting that: 1) The multi-model average TLT trend is always larger than the average observed TLT trend” and “2) As the trend fitting period increases ... average observed trends are

increasingly more unusual with respect to the multi-model distribution of forced trends.” Put another way, over longer periods of time that include a more robust signal, the discrepancy between model simulations and observed trends in the temperature of the lower troposphere increases, with the model overestimates being on the verge of statistical significance.

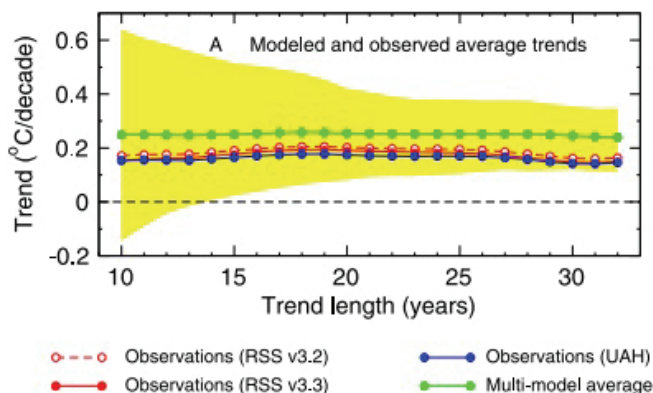


Figure 1.4.6.2.1. A comparison between modeled and observed trends in the average temperature of the lower atmosphere, for periods ranging from 10 to 32 years (during the period 1979 through 2010). The yellow is the 5-95 percentile range of individual model projections, the green is the model average, the red and blue are the average of the observations, as compiled by Remote Sensing Systems and University of Alabama in Huntsville respectively. Adapted from Santer, B.D., Mears, C., Doutriaux, C., Caldwell, P., Gleckler, P.J., Wigley, T.M.L., Solomon, S., Gillett, N.P., Ivanova, D., Karl, T.R., Lanzante, J.R., Meehl, G.A., Stott, P.A., Taylor, K.E., Thorne, P.W., Wehner, M.F., and Wentz, F.J. 2011. Separating signal and noise in atmospheric temperature changes: the importance of timescale. *Journal of Geophysical Research* **116**: 10.1029/2011JD016263.

Santer *et al.* (2013) performed “a multimodel detection and attribution study with climate model simulation output and satellite-based measurements of tropospheric and stratospheric temperature change,” using “simulation output from 20 climate models participating in phase 5 of the Coupled Model Intercomparison Project,” which “provides estimates of the signal pattern in response to combined anthropogenic and natural external forcing and the noise of internally generated variability.” Among other things, the 21 researchers report “most models do not replicate the size of the observed changes,” in that “the models analyzed underestimate the observed cooling of the lower stratosphere and overestimate the warming of the troposphere,” where warming, in their

opinion (Santer *et al.*, 2003; Hansen *et al.*, 2005), “is mainly driven by human-caused increases in well-mixed greenhouse gases,” and where “CMIP5 estimates of variability on 5- to 20-year timescales are (on average) 55-69% larger than in observations.”

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1.3.7 Oceans

The vast majority of the surface of the planet consists of oceans, which play a significant role in the modulation and control of Earth’s climate. As is true of other factors we have previously discussed, modeling of the oceans has proved to be a difficult task.

1.3.7.1 Atlantic Ocean

Keeley *et al.* (2012) note, “current state-of-the-art climate models fail to capture accurately the path of the Gulf Stream and North Atlantic Current,” and this model failure “leads to a warm bias near the North American coast, where the modeled Gulf Stream separates from the coast further north, and a cold anomaly to the east of the Grand Banks of Newfoundland, where the North Atlantic Current remains too zonal.”

Using a high-resolution coupled atmosphere-ocean model (HiGEM), described in detail by Shaffrey *et al.* (2009), Keeley *et al.* analyzed the impacts of the sea surface temperature (SST) biases created by the model in the North Atlantic in winter—approximately 8°C too cold to the east of the Grand Banks of Newfoundland and 6°C too warm near the east coast of North America—on the mean climatic state of the North Atlantic European region, along with the variability associated with those model-induced SST biases.

The three UK researchers say their results indicate the model-induced SST errors produce a mean sea-level pressure response “similar in

magnitude and pattern to the atmospheric circulation errors in the coupled climate model.” They also note “errors in the coupled model storm tracks and North Atlantic Oscillation, compared to reanalysis data, can also be explained partly by these SST errors.” Keeley *et al.* conclude, “both [1] the error in the Gulf Stream separation location and [2] the path of the North Atlantic Current around the Grand Banks play important roles in affecting the atmospheric circulation”; they further note “reducing these coupled model errors could improve significantly the representation of the large-scale atmospheric circulation of the North Atlantic and European region.”

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- 1.3.7.2 Pacific Ocean*
- Thompson and Kwon (2010) used a state-of-the-art coupled-atmosphere-ocean general circulation model known as the Community Climate System Model version 3 (CCSM3) to demonstrate that climate models have difficulty simulating interdecadal variations in the Pacific Ocean Circulation. The authors used the model with atmospheric radiative forcing fixed to 1990 levels and with medium-scale grid resolution. The model output was run for 700 years and a 100-year slice was selected starting with year 500.
- The model was unable to capture the natural characteristics of the Kuroshio Current and its extension (KE), resulting in a poor representation of climate variability in the North Pacific region. In nature, the mean position of the KE and the strongest sea surface temperature (SST) gradients are typically separated by 500 km. In the model control run, the two phenomena were coincident, resulting in excessively strong SST variations (Figure 1.3.7.2.1).
- The Kuroshio Current, like its Atlantic counterpart, the Gulf Stream, is a strong, narrow current in the Northwest Pacific that runs along Japan and continues into the North Pacific. The Oyashio Extension (OE) is a distinct current running along the Kurile Islands and Hokkaido. This current is analogous to the Labrador Current along Northeast North America. In the model, there was only one broad current, weaker than what is observed in nature. As a result, the SSTs are too warm near the Japan coast and too cold into the Pacific. The long-term SST variations were also too strong in the model.
- Interdecadal climate variations are internal forcings to Earth’s atmosphere system that, in concert with external forcing, will be important in determining what our future climate may look like. In order to create reasonable scenarios of climate change, these phenomena must be modeled accurately. Their strength and intensity also must be put into proper context with that of the total natural and greenhouse forcing in order to attribute the source of climate change.
- Many studies have shown the importance of SST gradients in contributing to the occurrence, strength, and location of atmospheric phenomena such as jet streams, storm tracks, and blocking (e.g., Kung *et al.* 1990; 1992; 1993). These phenomena, as well as the ocean circulations, are important in transporting heat and momentum poleward and maintaining the general circulation. Thus the reliability and accuracy of regional climate change model scenarios far from the Pacific (e.g., agriculturally important continental regions) will be strongly influenced by the model’s ability to capture Pacific region atmosphere and ocean circulations.
- As policymakers use climate simulations for the creation of policy and for planning purposes, it is important that biases in the climate models be acknowledged and understood. As Thompson and Kwon (2010) write, “it is important to note that CCSM3 is not unique in its poor representation of the KOE. The diffuse front and lack of distinction between the OE and KE is typical of low-resolution climate models.”
- In a paper published in the *Journal of Geophysical Research*, Guemas *et al.* (2012) also focused on this region of the Pacific Ocean, writing “the North Pacific region has a strong influence on North American and Asian climate.” They also state it is “the area with the worst performance in several state-of-the-art decadal climate predictions” and add that the failure of essentially all climate models “to

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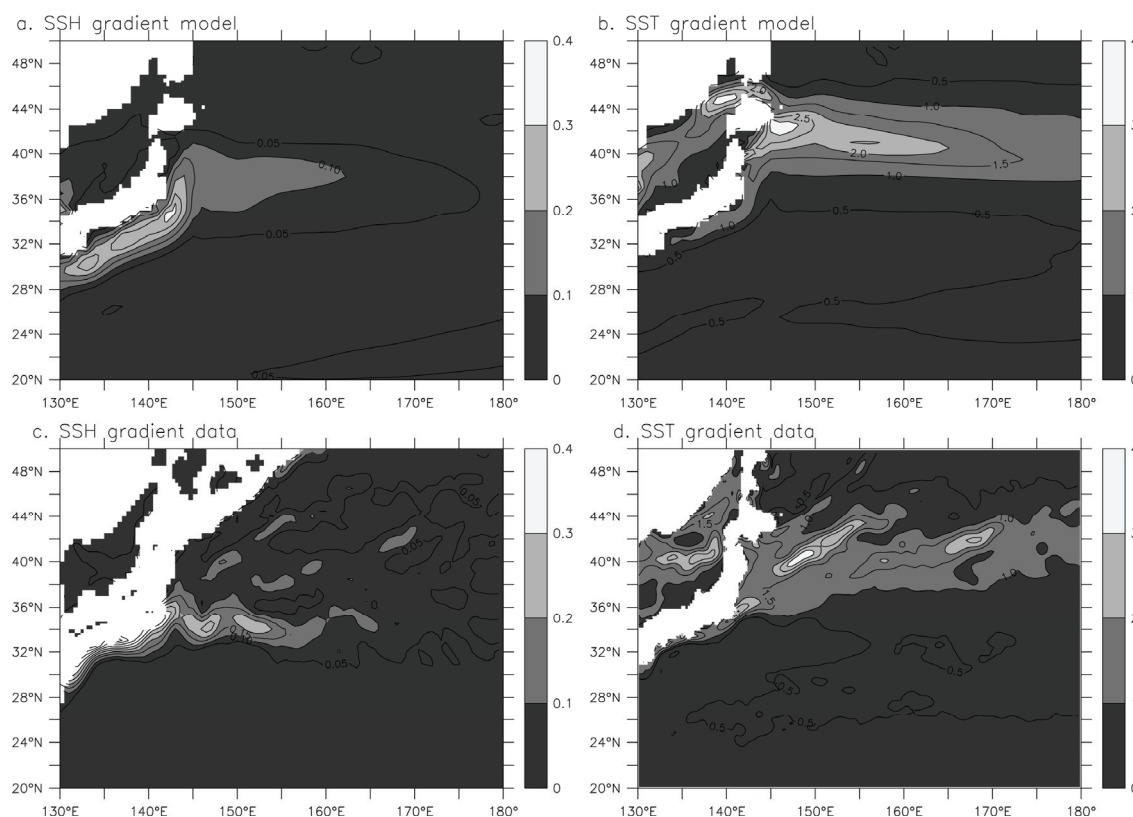


Figure 1.3.7.2.1. The gradients of sea surface height (SSH) and SST for the (a) and (b) control run—CCSM3, (c) generated by Maximenko and Niiler (2004), and (d) National Oceanic and Atmospheric Administration (NOAA). Reprinted with permission from Thompson, L. and Y.O. Kwon, 2010: An enhancement of Low-Frequency Variability in the Kuroshio-Oyashio Extension in CCM3 owing to Ocean Model Biases. *Journal of Climate* **23**, 6221-6233. DOI:10.1175/2010JCLI3402.1, Figure 1.

represent two major warm sea surface temperature events occurring around 1963 and 1968 largely contributes to this poor skill,” noting “understanding the causes of these major warm events is thus of primary concern to improve prediction of North Pacific, North American and Asian climate.”

The five researchers investigated “the reasons for this particularly low skill,” identifying and describing the two major warm events they say have been “consistently missed by every climate forecast system.” Based on their study of 11 observational data sets, Guemas *et al.* suggest the 1963 warm event “stemmed from the propagation of a warm anomaly along the Kuroshio-Oyashio extension” and the 1968 warm event “originated from the upward transfer of a warm water mass centered at 200 meters depth.” They conclude, “biases in ocean mixing processes present in many climate prediction models seem to explain the inability to predict these two major events.”

Although they acknowledge “reducing systematic

biases in ocean stratification and improving the representation of ocean mixing processes has been a long-standing effort,” Guemas *et al.* say their findings suggest allocating still more resources to “improving simulation of ocean mixing has the potential to significantly improve decadal climate prediction.”

Furtado *et al.* (2011) note the North Pacific Decadal Variability (NPDV) “is a key component in predictability studies of both regional and global climate change,” adding that “two patterns of climate variability in the North Pacific generally characterize NPDV.” These two “dominant modes,” as they refer to them, are the Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997) and the recently identified North Pacific Gyre Oscillation (NPGO; Di Lorenzo *et al.*, 2008). The scholars emphasize that given the links between the PDO and the NPGO and global climate, the accurate characterization and the degree of predictability of these two modes in coupled climate models is an important “open question in climate

dynamics.”

Furtado *et al.* investigate this situation by comparing the output from the 24 coupled climate models used in the IPCC AR4 with observational analyses of sea level pressure (SLP) and sea surface temperature (SST), based on SLP data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis Project (Kistler *et al.*, 2001), and SST data from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstruction SST dataset, version 3 (Smith *et al.*, 2008), both of which data sets contain monthly mean values from 1950–2008 gridded onto a global 2.5° x 2.5° latitude-longitude grid for SLP and a 2° x 2° grid for SST.

The four U.S. scientists report model-derived “temporal and spatial statistics of the North Pacific Ocean modes exhibit significant discrepancies from observations in their twentieth-century climate, most visibly for the second mode, which has significantly more low-frequency power and higher variance than in observations.” They also note the two dominant modes of North Pacific oceanic variability “do not exhibit significant changes in their spatial and temporal characteristics under greenhouse warming,” stating “the ability of the models to capture the dynamics associated with the leading North Pacific oceanic modes, including their link to corresponding atmospheric forcing patterns and to tropical variability, is questionable.”

There were even more “issues with the models,” Furtado *et al.* note. “In contrast with observations,” they report, “the atmospheric teleconnection excited by the El Niño–Southern Oscillation in the models does not project strongly on the AL [Aleutian low]–PDO coupled mode because of the displacement of the center of action of the AL in most models.” In addition, they note, “most models fail to show the observational connection between El Niño Modoki–central Pacific warming and NPO [North Pacific Oscillation] variability in the North Pacific.” They write, “the atmospheric teleconnections associated with El Niño Modoki in some models have a significant projection on, and excite the AL–PDO coupled mode instead.”

Furtado *et al.* conclude “for implications on future climate change, the coupled climate models show no consensus on projected future changes in frequency of either the first or second leading pattern of North Pacific SST anomalies” and “the lack of a consensus in changes in either mode also affects confidence in projected changes in the overlying

atmospheric circulation.” In addition, they note the lack of consensus they found “mirrors parallel findings in changes in ENSO behavior conducted by van Oldenborgh *et al.* (2005), Guilyardi (2006) and Merryfield (2006),” and they state these significant issues “most certainly impact global climate change predictions.”

Climate in the Southeast Pacific (SEP) near the coast of Peru and Chile, in the words of Zheng *et al.* (2011), “is controlled by complex upper-ocean, marine boundary layer and land processes and their interactions,” and they say variations in this system have “significant impacts on global climate,” citing Ma *et al.* (1996), Miller (1977), Gordon *et al.* (2000), and Xie (2004). However, they write, “it is well known that coupled atmosphere–ocean general circulation models tend to have systematic errors in the SEP region, including a warm bias in sea surface temperature and too little cloud cover,” as demonstrated by Mechoso *et al.* (1995), Ma *et al.* (1996), Gordon *et al.* (2000), McAvaney *et al.* (2001), Kiehl and Gent (2004), Large and Danabasoglu (2006), Wittenberg *et al.* (2006), and Lin (2007). Even though these biases have what Zheng *et al.* call “important impacts” on the simulation of Earth’s radiation budget and climate sensitivity, they note “it is still uncertain whether a similar bias is evident in most state-of-the-art coupled general circulation models [CGCMs] and to what extent the sea surface temperature [SST] biases are model dependent.”

Using 20-year (1980–1999) model runs of the Climate of the Twentieth Century simulations of the 19 CGCMs that figured prominently in the (IPCC) *Fourth Assessment Report* (AR4), Zheng *et al.* examined systematic biases in SSTs under the stratus cloud deck in the SEP and upper-ocean processes relevant to those biases, attempting to isolate their causes.

The four U.S. researchers discovered “pronounced warm SST biases in a large portion of the southeast Pacific stratus region ... in all models” and “negative biases in net surface heat fluxes ... in most of the models.” They found “biases in heat transport by Ekman currents largely contribute to warm SST biases both near the coast and the open ocean” and “in the coastal area, southwestward Ekman currents and upwelling in most models are much weaker than observed.” “In the open ocean,” they observed, “warm advection due to Ekman currents is overestimated.” They write, “negative biases (cooling the ocean) in net surface heat flux” and “positive biases in shortwave radiation” are found

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in most models, because most models “do not generate sufficient stratus clouds” and “underestimate alongshore winds and coastal upwelling.”

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1.3.7.3 Indian Ocean

Nagura *et al.* (2013) explain the term “Seychelles Dome” refers to the shallow climatological thermocline in the southwestern Indian Ocean, “where ocean wave dynamics efficiently affect sea surface temperature [SST], allowing SST anomalies to be predicted up to 1–2 years in advance.” They also indicate this ability is significant: “The anomalous SSTs in the dome region subsequently impact various atmospheric phenomena, such as tropical cyclones (Xie *et al.*, 2002), the onset of the Indian summer monsoon (Joseph *et al.*, 1994; Annamalai *et al.*, 2005) and precipitation over India and Africa (Annamalai *et al.*, 2007; Izumo *et al.*, 2008).”

They note “Yokoi *et al.* (2009) examined the outputs from models used in phase three of the Coupled Model Intercomparison Project (CMIP3) and found that many CMIP3 models have serious biases in this region.” Hoping to find some improvement in the four years since Yokoi *et al.* conducted their research, Nagura *et al.* examined model biases associated with the Seychelles Dome using state-of-the-art ocean-atmosphere coupled general circulation models (CGCMs), “including those from phase five of the Coupled Model Intercomparison Project (CMIP5).”

Nagura *et al.* report several of the tested models “erroneously produce an upwelling dome in the eastern half of the basin, whereas the observed Seychelles Dome is located in the southwestern tropical Indian Ocean.” They also note “the annual mean Ekman pumping velocity in these models is found to be almost zero in the southern off-equatorial region,” which “is inconsistent with observations, in which Ekman upwelling acts as the main cause of the Seychelles Dome.” Moreover, “in the models reproducing an eastward-displaced dome, easterly biases are prominent along the equator in boreal summer and fall, which result in shallow thermocline biases along the Java and Sumatra coasts via Kelvin wave dynamics and a spurious upwelling dome in the region.” In a revealing final assessment of their findings, Nagura *et al.* conclude “compared to the CMIP3 models, the CMIP5 models are even worse in simulating the dome longitudes.”

The Indian Ocean Dipole (IOD) is an irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean. Cai and Cowan (2013) note “in most models, IOD peak-season amplitudes are systematically larger than that of the observed,” and they say “understanding the cause of this bias is ... essential for alleviating model errors and reducing uncertainty in climate projections.”

The two Australian researchers analyzed sea surface temperatures (SSTs), thermocline characteristics (20°C isotherm depth), and zonal wind and precipitation outputs from 23 CMIP3 models and 33 CMIP5 models that attempted to simulate these climatic features over the last half of the twentieth century, after which they compared the model simulations with real-world observations. Cai and Cowan report “most models generate an overly deep western Indian Ocean thermocline that results in an unrealistic upward slope toward the eastern tropical Indian Ocean” and “the unrealistic thermocline structure is associated with too strong a mean easterly wind over the equatorial Indian Ocean, which is in turn supported by a slightly stronger mean west minus east SST gradient, reinforced by the unrealistic thermocline slope.”

They conclude, “these biases/errors have persisted in several generations of models,” such that “there is no clear improvement from CMIP3 to CMIP5.”

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- 1.3.7.4 Equatorial/Tropical Regions*
- Wan *et al.* (2011) state “the notorious tropical bias problem in climate simulations of global coupled general circulation models (e.g., Mechoso *et al.*, 1995; Latif *et al.*, 2001; Davey *et al.*, 2002; Meehl *et al.*, 2005) manifests itself particularly strongly in the tropical Atlantic,” and “while progress towards reducing tropical climate biases has been made in the tropical Pacific over the past decades (e.g., Deser *et al.*, 2006), little or no progress has been made in the tropical Atlantic (Breugem *et al.*, 2006; Richter and Xie, 2008; Wahl *et al.*, 2009).” They write, “the climate bias problem is still so severe that one of the most basic features of the equatorial Atlantic Ocean—the eastward shoaling thermocline—cannot be reproduced by most of the Intergovernmental Panel on Climate Change (IPCC) assessment report (AR4) models,” citing Richter and Xie (2008).
- In their own investigation of the subject, Wan *et al.* “show that the bias in the eastern equatorial Atlantic has a major effect on sea-surface temperature (SST) response to a rapid change in the Atlantic Meridional Overturning Circulation (AMOC).” They do so by exemplifying the problem “through an inter-model comparison study of tropical Atlantic response to an abrupt change in [the] AMOC using the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Climate Model (CM2.1) and the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3)” and dissecting the oceanic mechanisms responsible for the difference in the models’ SST responses.
- Their analysis demonstrates the different SST responses of the two models are “plausibly attributed to systematic differences in the simulated tropical Atlantic ocean circulation.” The ultimate implication of Wan *et al.*’s findings is, in their words, that “in order to accurately simulate past abrupt climate changes and project future changes, the bias in climate models must be reduced.”
- Shin and Sardeshmukh (2011) note there is “increased interest in the ability of climate models to simulate and predict surface temperature and precipitation changes on sub-continental scales,” and they state these regional trend patterns “have been strongly influenced by the warming pattern of the tropical oceans,” which suggests correctly simulating the warming pattern of the tropical oceans is a prerequisite for correctly simulating sub-continental-scale warming patterns.
- In exploring this subject further, Shin and Sardeshmukh compared multi-model ensemble simulations of the last half-century with corresponding observations, focusing on the world’s tropical oceans, as well as the land masses surrounding the North Atlantic Ocean, including North America, Greenland, Europe, and North Africa. This was done, as they describe it, using “all available coupled [atmosphere-ocean] model simulations of the period 1951–1999 from 18 international modeling centers, generated as part of the IPCC’s 20th century climate simulations with prescribed time-varying radiative forcings associated with greenhouse gases, aerosols, and solar variations.”
- The two researchers report “the tropical oceanic warming pattern is poorly represented in the coupled

simulations,” and they state their analysis “points to model error rather than unpredictable climate noise as a major cause of this discrepancy with respect to the observed trends.” They found “the patterns of recent climate trends over North America, Greenland, Europe, and North Africa are generally not well captured by state-of-the-art coupled atmosphere-ocean models with prescribed observed radiative forcing changes.”

Commenting on their work, Shin and Sardeshmukh write, “the fact that even with full atmosphere-ocean coupling, climate models with prescribed observed radiative forcing changes do not capture the pattern of the observed tropical oceanic warming suggests that either the radiatively forced component of this warming pattern was sufficiently small in recent decades to be dwarfed by natural tropical SST variability, or that the coupled models are misrepresenting some important tropical physics.” Since the greenhouse-gas forcing of climate “in recent decades” is claimed by the IPCC to have been unprecedented over the past millennium or more, it would appear the models are indeed “misrepresenting some important tropical physics.”

Li and Xie (2012) write, “state-of-the-art coupled ocean-atmosphere general circulation models (CGCMs) suffer from large errors in simulating tropical climate, limiting their utility in climate prediction and projection.” Describing the size of the several errors, they say they “are comparable or larger in magnitude than observed interannual variability and projected change in the 21st century.”

The two researchers say the “well-known errors” include “too weak a zonal SST gradient along the equatorial Atlantic,” citing Davey *et al.* (2002) and Richter and Xie (2008); “an equatorial cold tongue that penetrates too far westward in the Pacific,” citing Mechoso *et al.* (1995) and de Szoeke and Xie (2008); and “too warm SSTs over the tropical Southeast Pacific and Atlantic, and a spurious double intertropical convergence zone,” citing Lin (2007). They point out “these errors have persisted in several generations of models for more than a decade.”

Closer inspection of zonal SST profiles along the equator is found by Li and Xie to reveal “basin-wide offsets, most obvious in the Indian (Saji *et al.*, 2006) but visible in the Pacific (de Szoeke and Xie, 2008), and Atlantic (Richter and Xie, 2008) Oceans.” They add “it is unclear whether such basin-wide offset errors are limited to individual tropical basins or shared among all the basins.”

Li and Xie then “examine the Climate of the

Twentieth Century (20C3M) simulations (also termed as ‘historical’ runs) from 22 CMIP3 and 21 CMIP5 CGCMs for a 30-year period of 1970–99, together with their available Atmospheric Model Intercomparison Project (AMIP) runs that are forced with the observed SST.” They find two types of tropical-wide offset biases. One of them “reflects the tropical mean SST differences from observations and among models, with a broad meridional structure and of the same sign across all basins of up to 2°C in magnitude,” while the other “is linked to inter-model variability in the cold tongue temperatures in the equatorial Pacific and Atlantic.”

In further describing their findings, the two researchers write “the first-type offset error is ascribed to atmospheric model representation of cloud cover, with cloudy models biasing low in tropical-wide SST,” while “the second type originates from the diversity among models in representing the thermocline depth, with deep thermocline models biasing warm in the equatorial cold tongues.”

Also addressing the ability of CGCMs to accurately model the equatorial and tropical regions, Zheng *et al.* (2012) note “the equatorial Pacific is observed to have a minimum sea surface temperature (SST) that extends from the west coasts of the Americas into the central Pacific,” and this “extension of cool water is commonly referred to as the cold tongue (Wyrski, 1981).” They state “it is generally argued that the Pacific cold tongue is maintained by horizontal advection of cold water from the east and by upwelling of cold water from the subsurface.” The three researchers proceed to examine “the contribution of ocean dynamics to sea surface temperature biases in the eastern Pacific cold tongue region in fifteen coupled general circulation models (CGCMs) participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4),” analyzing “twenty years (1980–1999) of the twentieth-century climate simulations from each model.”

Zheng *et al.* find “errors in both net surface heat flux and total upper ocean heat advection significantly contribute to the excessive cold tongue in the equatorial Pacific” and conclude “the stronger heat advection in the models is caused by overly strong horizontal heat advection associated with too strong zonal currents, and overly strong vertical heat advection due to excessive upwelling and the vertical gradient of temperature.” They note “the Bjerknes feedback in the coupled models is shown to be weaker than in observations, which may be related to

the insufficient response of surface zonal winds to SST in the models and an erroneous subsurface temperature structure,” such that “the cold tongue becomes colder than the cold tongue in the observations.” Zheng *et al.* conclude “more work is needed on the role of the ocean model and ocean-atmosphere feedback in the growth of the double-ITCZ pattern.”

In looking at equatorial SSTs, Vanniere *et al.* (2013) state “the cold equatorial SST bias in the tropical Pacific that is persistent in many coupled OAGCMs [Ocean-Atmosphere Global Climate Models] severely impacts the fidelity of the simulated climate and variability in this key region, such as the ENSO [El Niño-Southern Oscillation] phenomenon.” More specifically, they note “the seasonal equatorial cold tongue extends too far west, is too cold in the east Pacific and is associated with too strong trade winds,” citing Davey *et al.* (2001), AchutaRao and Sperber (2006), and Lin (2007). In addition, they write, “a warm SST bias is observed near the coast of South America,” which is “associated with a lack of low clouds and deficient winds.” And they note “mean state biases relevant to ENSO also include too strong easterlies in the west Pacific and the double ITCZ [Intertropical Convergence Zone] syndrome,” citing Lin (2007) and de Szoeke and Xie (2008).

In attempting to unscramble and resolve these many problems, Vanniere *et al.* (2013) used seasonal re-forecasts or hindcasts to “track back” the origin of the major cold bias, so that “a time sequence of processes involved in the advent of the final mean state errors can then be proposed,” applying this strategy to the ENSEMBLES-FP6 project multi-model hindcasts of the last decades. The researchers discovered “the models are able to reproduce either El Niño or La Niña close to observations, but not both.” Therefore, they conclude, “more work is needed to understand the origin of the zonal wind bias in models,” and, in this regard, “understanding the dynamical and thermodynamical mechanisms that drive the tropical atmosphere is required both to alleviate OAGCM errors and to describe the full extent of the atmosphere’s role in tropical variability, such as ENSO.”

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1.3.7.5 Southern Ocean

Weijer *et al.* (2012) note “the Southern Ocean is a region of extremes: it is exposed to the most severe winds on the Earth (Wunsch, 1998), the largest ice shelves (Scambos *et al.*, 2007), and the most extensive seasonal sea ice cover (Thomas and Dieckmann, 2003).” They indicate various interactions among the atmosphere, ocean, and cryosphere in this region “greatly influence the dynamics of the entire climate system through the formation of water masses and the sequestration of heat, freshwater, carbon, and other properties (Rintoul *et al.*, 2001).”

Against this backdrop, Weijer *et al.* “explored several key aspects of the Southern Ocean and its climate in the new Community Climate System Model, version 4 (CCSM4),” including “the surface climatology and inter-annual variability, simulation of key climate water masses (Antarctic Bottom Water [AABW], Subantarctic Mode Water [SAMW], and Antarctic Intermediate Water [AAIW]), the transport and structure of the Antarctic Circumpolar Current [ACC], and inter-basin exchange via the Agulhas and

Tasman leakages and at the Brazil-Malvinas Confluence [BMC].”

The nine researchers find “the CCSM4 has varying degrees of accuracy in the simulation of the climate of the Southern Ocean when compared with observations.” Results of this comparison include: (1) “the seasonally ice-covered regions are mildly colder ($\Delta\text{SST} > -2^\circ\text{C}$) than observations,” (2) “sea ice extent is significantly larger than observed,” (3) “north of the seasonal ice edge, there is a strong ($-4^\circ\text{C} < \Delta\text{SST} < -1^\circ\text{C}$) cold bias in the entire Pacific sector south of 50°S and in the western Australian-Antarctic Basin,” (4) “positive biases ($1^\circ < \Delta\text{SST} < 4^\circ\text{C}$) are found in the Indian and Atlantic sectors of the Southern Ocean,” (5) “significant differences are found in the Indian and Pacific sectors north of the ACC, with the CCSM4 model being too cold ($< -2^\circ\text{C}$) and fresh (< 0.3 psu),” (6) “AABW adjacent to the Antarctic continent is too dense,” (7) “North Atlantic Deep Water is too salty (> 0.2 psu),” (8) “in the Indian and Pacific sectors of the Southern Ocean, north of 50°S and below 3000 meters, the too-salty AABW penetrates northward, resulting in a denser-than-observed abyssal ocean in CCSM4,” (9) “the model underestimates the depth of the deep winter mixed layers in the Indian and eastern Pacific sectors of the Southern Ocean north of the ACC,” (10) “in the southern Tasman Sea and along the eastern Indian Ocean boundary ... the model mixed layer depth is deeper than observed by more than 400 meters,” (11) “in all sectors of the Southern Ocean, Model CFC-11 concentrations in the lower thermocline and intermediate waters are lower than observed,” (12) “model CFC-11 concentrations in the deep ocean (below 2000 meters) are lower than observed in the basins adjacent to the Antarctic continent,” (13) “model surface CFC-11 concentrations are higher than observed,” (14) “the production of overflow waters in the Ross Sea is too low by about a factor of 2 relative to the limited observations,” (15) “the depth at which the product water settles was also shown to be too shallow by about a factor of 2,” (16) “the subtropical gyre of the South Atlantic is too strong by almost a factor of 2, associated with a strong bias in the wind stress,” (17) the mean position of the BMC is too far south in the CCSM4,” and (18) “the model variability in the position of the BMC is significantly less than observations.”

Weijer *et al.* conclude that as the CCSM4 currently stands, it “may underestimate the sequestration of heat, carbon, and other properties to the interior ocean,” such that its parameterizations

may “lead to significant biases in the representation of the Southern Ocean and its climate.”

According to Sallee *et al.* (2013), “the Southern Ocean is the dominant anthropogenic carbon sink of the world’s oceans and plays a central role in the redistribution of physical and biogeochemical properties around the globe,” citing Sarmiento *et al.* (2004). They add “one of the most pressing issues in oceanography is to understand the rate, the structure and the controls of the water mass overturning circulation in the Southern Ocean and to accurately represent these aspects in climate models.” Focusing on five water masses crucial for the Southern Ocean overturning circulation—surface subTropical Water (TW), Mode Water (MW), Intermediate Water (IW), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (AABW)—Sallee *et al.* studied the ability of 21 of the CMIP5 models to simulate what they describe as the most basic properties of each of these water masses: temperature, salinity, volume, and outcrop area.

The authors describe several important findings. They note, “the water masses of the Southern Ocean in the CMIP5 models are too warm and light over the entire water column,” with the largest biases being found in the ventilated layers, and “the mode water layer is poorly represented in the models and both mode and intermediate water have a significant fresh bias.” They further find, “in contrast to observations (e.g., Rintoul, 2007), bottom water is simulated to become slightly saltier” and “when compared to observation-based reconstructions,” the models “exhibit a slightly larger rate of overturning at shallow to intermediate depths, and a slower rate of overturning deeper in the water column.” Given such discrepancies, the seven scientists conclude “many of the biases and future changes identified in this study are expected to have significant impacts on the marine carbon cycle.” These biases and the changes they spawn are not trivial and must be corrected before they are used to forecast the future of the overturning circulation of the Southern Ocean and its impact on global climate.

Heuze *et al.* (2013) point out “the ability of a model to adequately depict bottom water formation is crucial for accurate prediction of changes in the thermohaline circulation,” citing Hay (1993). They note, however, “this process is particularly challenging to represent in the current generation of climate models” and “the last generation of models in CMIP3 poorly represented Southern Ocean transport and heat fluxes,” citing Russell *et al.* (2006).

Heuze *et al.* assessed “Southern Ocean potential temperature, salinity, density and sea ice concentration in fifteen CMIP5 historical simulations (means of the twenty August monthly mean fields from 1986 to 2005),” comparing the 20-year mean model fields with historical hydrographic data and Hadley Centre sea ice climatologies. They note no model reproduces the process of Antarctic bottom water formation accurately, for “instead of forming dense water on the continental shelf and allowing it to spill off,” the models “present extensive areas of deep convection, thus leading to an unrealistic unstratified open ocean.”

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1.3.7.6 Sea Ice

Writing about how well the models of more than a decade ago simulated changes in sea ice, Holland (2001) states “the present situation with respect to the state-of-the-art global climate models is that some physical processes are absent from the models and, with the rather coarse-resolution grids used, some physical processes are ill resolved ... and therefore in practical terms missing from the simulations.” Holland thus questions “whether the simulations obtained from such models are in fact physically meaningful” and conducted an analysis to determine the difference in model evolution of sea ice cover using a relatively coarse-resolution grid versus a fine-resolution grid, with specific emphasis on the presence and treatment of a mesoscale ocean eddy and its influence on sea ice cover.

Resolving the ocean eddy field using the fine-resolution model was found to have a measurable impact on sea ice concentration, implying a “fine-resolution grid may have a more efficient atmosphere-sea ice-ocean thermodynamic exchange than a coarse one.” Holland concludes his study demonstrated “yet again that coarse-resolution coupled climate models are not reaching fine enough resolution in the polar regions of the world ocean to claim that their numerical solutions have reached convergence.”

Two years later, the situation had not improved much. Laxon *et al.* (2003) used an eight-year time series (1993–2001) of Arctic sea-ice thickness derived from measurements of ice freeboard made by 13.8-GHz radar altimeters carried aboard ERS-1 and 2 satellites to determine the mean thickness and variability of Arctic sea ice between latitudes 65 and 81.5°N, a region covering the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. Mean winter sea-ice thickness over the region was found to be 2.73 meters with a standard deviation of $\pm 9\%$ of the average, a variability 50 percent greater than predicted by climate models “and

probably more,” the authors state. They report their analysis “excludes variability that occurs over timescales of longer than a decade.”

Further comparing their observations with model projections, the authors noted several discrepancies. First, Laxon *et al.* specifically note their observations “show an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models,” clearly indicating the models do not reproduce reality very well in this regard. Second, they state “the interannual variability in thickness [9%] compares with a variability in mean annual ice extent of 1.7% during the same period,” which, in the words of the authors, “undermines the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent.” Third, concerning the origin of Arctic sea-ice thickness variability, the authors discovered “a significant ($R^2 = 0.924$) correlation between the change in the altimeter-derived thickness between consecutive winters, and the melt season length during the intervening summer.” This “observed dominant control of summer melt on the interannual variability of mean ice thickness,” according to the researchers, “is in sharp contrast with the majority of models, which suggest that ice thickness variability in the Arctic Ocean is controlled mainly by wind and ocean forcing.” Fourth, the authors’ data demonstrate “sea ice mass can change by up to 16% within one year,” which “contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming,” representing still another failure of the models.

Laxon *et al.* close their analysis by stating their results “show that errors are present in current simulations of Arctic sea ice,” concluding, “until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and future, changes in Arctic ice cover will be open to question.”

Eisenman *et al.* (2007) used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different global climate models evaluated for the IPCC’s *Fourth Assessment Report*. Results indicate there was a 40 Wm^{-2} spread among the models in terms of their calculated downward longwave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from one to more than ten meters.

They note the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were “forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes?”

The three researchers say “a frequently used approach” to resolving this problem “is to tune the parameters associated with the ice surface albedo” to get a more realistic answer. “In other words,” as they continue, “errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components.” They conclude “the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields” and, therefore, “the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice.”

Kwok (2011) notes near the midpoint of the last decade, simulations of Arctic Ocean sea ice characteristics produced by the climate models included in the World Climate Research Programme’s Coupled Model Intercomparison Project phase 3 (CMIP3) were far from what might have been hoped. Specifically, he writes “Zhang and Walsh (2006) note that even though the CMIP3 models capture the negative trend in sea ice area, the inter-model scatter is large,” “Stroeve *et al.* (2007) show that few models exhibit negative trends that are comparable to observations” and “Eisenman *et al.* (2007) conclude that the results of current CMIP3 models cannot be relied upon for credible projections of sea ice behavior.”

In his more recent analysis of the subject, based on the multi-model data set of Meehl *et al.* (2007), Kwok, a researcher at the Jet Propulsion Laboratory, compares CMIP3 model simulations “with observations of sea ice motion, export, extent, and thickness and analyzes fields of sea level pressure and geostrophic wind of the Arctic Ocean.” Kwok’s analysis demonstrated “the skill of the CMIP3 models (as a group) in simulation of observed Arctic sea ice motion, Fram Strait export, extent, and thickness between 1979 and 2008 seems rather poor.” He notes “model-data differences and inter-model scatter of the sea ice parameters in the summarizing statistics are high” and “the spatial pattern of Arctic sea ice thickness, a large-scale slowly varying climatic

feature of the ice cover, is not reproduced in a majority of the models.” Consequently, he writes, “the models will not get the main features of natural sea ice variability that may be dominating recent sea ice extent declines as well as the long-term greenhouse response.”

“Because the model simulations have difficulties reproducing the mean patterns of Arctic circulation and thickness,” Kwok concludes, his analysis suggests there are “considerable uncertainties in the projected rates of sea ice decline even though the CMIP3 data set agrees that increased greenhouse gas concentrations will result in a reduction of Arctic sea ice area and volume.”

The most recent investigation into the topic was conducted by Turner *et al.* (2013). The authors state “Phase 5 of CMIP (CMIP5) will provide the model output that will form the basis of the *Fifth Assessment Report* (AR5) of the IPCC,” and they therefore thought it important to determine how well these models represent reality. They set out to examine “the annual cycle and trends in Antarctic sea ice extent (SIE) for 18 models used in phase 5 of the Coupled Model Intercomparison Project that were run with historical forcing for the 1850s to 2005.”

According to the five researchers, their examination indicated “the majority of models have too small of an SIE at the minimum in February” and “several of the models have less than two-thirds of the observed SIE at the September maximum. They further note, “in contrast to the satellite data, which exhibit a slight increase in SIE, the mean SIE of the models over 1979–2005 shows a decrease in each month”; “the models have very large differences in SIE over 1860–2005”; and “the negative SIE trends in most of the model runs over 1979–2005 are a continuation of an earlier decline, suggesting that the processes responsible for the observed increase over the last 30 years are not being simulated correctly.”

Turner *et al.* conclude “many of the SIE biases in the CMIP3 runs remain in CMIP5.” More particularly, for example, they state, “as with CMIP3, the models do not simulate the recent increase in Antarctic SIE observed in the satellite data.”

Confirming the results of Turner *et al.* (2013), Swart and Fyfe (2013) examined the consistency between satellite observations and CMIP5 climate model projections of the evolution of Antarctic sea ice extent. They note, “The CMIP5 multimodel ensemble mean shows a large negative trend in annual mean sea ice area of -3.0×10^{11} m²/decade over the historical period” and “By contrast, the

observations show a statistically significant positive trend of $1.39 \pm 0.82 \times 10^{11} \text{ m}^2/\text{decade}$ (95% confidence interval accounting for serial correlation).” (See Figure 1.3.7.6.1.)

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1.3.8 Soil Moisture

Climate models have long indicated that CO₂-induced global warming will increase evapotranspiration, causing decreases in soil moisture content that may offset modest increases in continental precipitation and lead to greater aridity in both water-limited natural ecosystems and lands devoted to agriculture

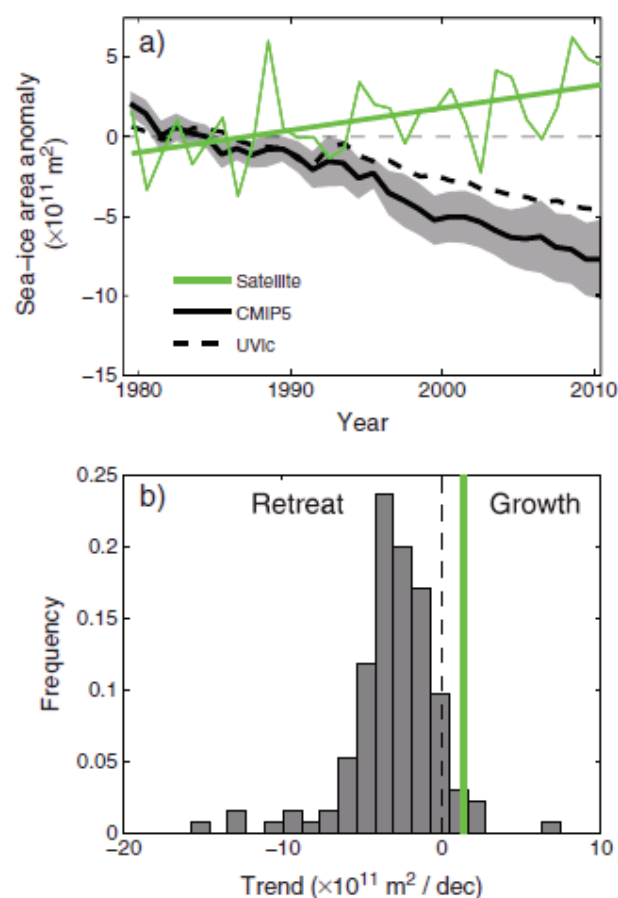


Figure 1.3.7.6.1. (a) Annual mean Antarctic sea ice area anomaly relative to the 1979–1989 base period, for satellite observations using the NASATEAM algorithm, the ensemble mean of 38 CMIP5 models (with a total of 135 realizations, listed in the supporting information), with the envelope indicating the 95% confidence interval, and the University of Victoria (UVic) model. The thick green curve is the linear least squares fit to the observed anomalies. (b) Distribution of linear trends in annual mean sea ice area for the CMIP5 models and the observed trend. Adapted from Figure 1 of Swart, N.C. and Fyfe, J.C., 2013. The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters* **40**: 10.1002/grl.50820.

(Manabe and Wetherald, 1986; Rind, 1988; Gleick, 1989; Vlades *et al.*, 1994; Gregory *et al.*, 1997; Komescu *et al.*, 1998). This section examines pertinent scientific literature to assess this claim.

In a turn-of-the century evaluation of how climate modelers had progressed in their efforts to improve their simulations of soil moisture content over the prior few years, Srinivasan *et al.* (2000)

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examined “the impacts of model revisions, particularly the land surface representations, on soil moisture simulations, by comparing the simulations to actual soil moisture observations.” They write, “the revised models do not show any systematic improvement in their ability to simulate observed seasonal variations of soil moisture over the regions studied.” They also note, “there are no indications of conceptually more realistic land surface representations producing better soil moisture simulations in the revised climate models.” They report a “tendency toward unrealistic summer drying in several models,” which they note was “particularly relevant in view of the summer desiccation projected by GCMs considered in future assessments of climate change.”

Although Srinivasan *et al.* report “simpler land-surface parameterization schemes are being replaced by conceptually realistic treatments,” as the climate modeling enterprise evolves, they note “improvements gained by such changes are ... not very apparent.”

A similar assessment was supplied that year by Robock *et al.* (2000), who developed a massive collection of soil moisture data for more than 600 stations from a wide variety of climatic regimes found within the former Soviet Union, China, Mongolia, India, and the United States. In describing these data sets they also state an important ground rule. Sometimes, they note, “the word ‘data’ is used to describe output from theoretical model calculations, or values derived from theoretical analysis of radiances from remote sensing.” However, they state, “we prefer to reserve this word for actual physical observations,” noting “all the data in our data bank are actual *in situ* observations.”

This distinction is important, for one of the illuminating analyses Robock *et al.* performed with their data was to check summer soil moisture trends simulated by the Geophysical Fluid Dynamics Laboratory’s general circulation model of the atmosphere as forced by transient CO₂ and tropospheric sulfate aerosols for specific periods and regions for which they had actual soil moisture data. They found, “although this model predicts summer desiccation in the next century, it does not in general reproduce the observed upward trends in soil moisture very well,” a mammoth understatement considering the predictions and observations go in opposite directions. As noted elsewhere in their paper, “in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the

longest records, summer soil moisture in the top 1 m has increased while temperatures have risen.”

Another important report on the subject is presented five years later, again by Robock *et al.* (2005), who note “most global climate model simulations of the future, when forced with increasing greenhouse gases and anthropogenic aerosols, predict summer desiccation in the midlatitudes of the Northern Hemisphere (e.g., Gregory *et al.*, 1997; Wetherald and Manabe, 1999; Cubasch *et al.*, 2001),” adding “this predicted soil moisture reduction, the product of increased evaporative demand with higher temperatures overwhelming any increased precipitation, is one of the gravest threats of global warming, potentially having large impacts on our food supply.”

With the explicit intent “to evaluate these model simulations,” the three American and two Ukrainian scientists present “the longest data set of observed soil moisture available in the world, 45 years of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April-October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958-2002.” As they describe it, “the observations show a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades,” noting “even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals.”

In light of these real-world observations, Robock *et al.* note “although models of global warming predict summer desiccation in a greenhouse-warmed world, there is no evidence for this in the observations yet, even though the region has been warming for the entire period.” In attempting to explain this dichotomy, they state the real-world increase in soil moisture content may have been driven by a downward trend in evaporation caused by the controversial “global dimming” hypothesis (Liepert *et al.*, 2004). Alternatively, we offer it may have been driven by the well-known anti-transpirant effect of atmospheric CO₂ enrichment, which tends to conserve water in the soils beneath crops and thereby leads to enhanced soil moisture contents, as has been demonstrated in a host of experiments conducted in real-world field situations.

One especially outstanding study in this regard is that of Zaveleta *et al.* (2003), who tested the hypothesis that soil moisture contents may decline in

a CO₂-enriched and warmer world, in a two-year study of an annual-dominated California grassland at the Jasper Ridge Biological Preserve, Stanford, California, USA, where they delivered extra heating to a number of free-air CO₂ enrichment (FACE) plots (enriched with an extra 300 ppm of CO₂) via IR heat lamps suspended over the plots that warmed the surface of the soil beneath them by 0.8-1.0°C.

The individual effects of atmospheric CO₂ enrichment and soil warming were of similar magnitude, and acting together they enhanced mean spring soil moisture content by about 15 percent over that of the control treatment. The effect of CO₂ was produced primarily as a consequence of its ability to cause partial stomatal closure and thereby reduce season-long plant water loss via transpiration. In the case of warming, there was an acceleration of canopy senescence that further increased soil moisture by reducing the period of time over which transpiration losses occur, all without any decrease in total plant production.

Zaveleta *et al.* note their findings “illustrate the potential for organism-environment interactions to modify the direction as well as the magnitude of global change effects on ecosystem functioning.” Whereas model projections suggest vast reaches of agricultural land will dry up and be lost to profitable production in a CO₂-enriched world of the future, this study suggests just the opposite could occur. As the six researchers describe it, “we suggest that in at least some ecosystems, declines in plant transpiration mediated by changes in phenology can offset direct increases in evaporative water losses under future warming.”

Guo and Dirmeyer (2006) compared soil moisture simulations made by 11 models in the Second Global Soil Wetness Project, a multi-institutional modeling research activity intended to produce a complete multi-model set of land surface state variables and fluxes by using land surface models driven by the 10-year period of data provided by the International Satellite Land Surface Climatology Project Initiative II, against real-world observations made on the top meter of grassland and agricultural soils located within parts of the former Soviet Union, the United States (Illinois), China, and Mongolia that are archived in the Global Soil Moisture Data Bank.

According to the authors, “simulating the actual values of observed soil moisture is still a challenging task for all models,” as they note “both the root mean square of errors (RMSE) and the spread of RMSE across models are large” and “the absolute values of

soil moisture are poorly simulated by most models.” In addition, they report “within regions there can be tremendous variations of any model to simulate the time series of soil moisture at different stations.”

Guo and Dirmeyer suggest the errors and variations are serious problems for the models. First, the two researchers write “the land surface plays a vital role in the global climate system through interactions with the atmosphere.” They also note “accurate simulation of land surface states is critical to the skill of weather and climate forecasts” and soil moisture “is the definitive land surface state variable; key for model initial conditions from which the global weather and climate forecasts begin integrations, and a vital factor affecting surface heat fluxes and land surface temperature.”

Li *et al.* (2007) compared soil moisture simulations derived from the IPCC’s AR4 climate models, which were driven by observed climate forcings, for the period 1958–1999 with actual measurements of soil moisture made at more than 140 stations or districts in the mid-latitudes of the Northern Hemisphere. The latter were averaged in such a way as to yield six regional results: one each for the Ukraine, Russia, Mongolia, Northern China, Central China, and Illinois (USA). According to the three researchers, the models showed realistic seasonal cycles for the Ukraine, Russia, and Illinois but “generally poor seasonal cycles for Mongolia and China.” In addition, they report the Ukraine and Russia experienced soil moisture increases in summer “that were larger than most trends in the model simulations.” The researchers found “only two out of 25 model realizations show trends comparable to those observations,” and the two realistic model-derived trends were “due to internal model variability rather than a result of external forcing,” which means the two reasonable matches were in fact accidental.

Noting further “changes in precipitation and temperature cannot fully explain soil moisture increases for [the] Ukraine and Russia,” Li *et al.* write, “other factors might have played a dominant role on the observed patterns for soil moisture.” They mention solar dimming, plus the fact that in response to elevated atmospheric CO₂ concentrations, “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,” reporting this phenomenon was detected in continental river runoff data by Gedney *et al.* (2006).

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Christensen and Boberg (2012) compared monthly mean temperatures projected by 34 global climate models included in phase 5 of the Coupled Model Intercomparison Project (CMIP5) with observations from the University of East Anglia's Climatic Research Unit for 26 different regions covering all major land areas of the world for the period 1961–2000, for which they employed quantile-quantile (q-q) diagrams. This revealed the existence of “a warm period positive temperature dependent bias” for “many of the models with many of the chosen climate regions”; the magnitude of this temperature dependence varied considerably among the models.

Analyzing the role of this difference as “a contributing factor for some models to project stronger regional warming than others,” the two scientists found “models with a positive temperature dependent bias tend to have a large projected temperature change” and “these tendencies increase with increasing global warming level.” In addition, they state this situation “appears to be linked with the ability of models to capture complex feedbacks accurately,” noting in particular that land-surface/atmosphere interactions are treated differently and with different degrees of realism among the various models they investigated and “soil moisture-temperature feedbacks are relevant for temperature extremes in a large fraction of the globe.”

Christensen and Boberg conclude, “accepting model spread as a way to portray uncertainty of the projection estimate may result in an overestimation of the projected warming and at the same time indicate little model agreement on the mean value.” They note “a non-negligible part” of this overestimation “is due to model deficiencies” that have yet to be overcome.

In light of the observations discussed above, it would appear almost all climate models employed to date have greatly erred with respect to what Robock *et al.* (2005) describe as “one of the gravest threats of global warming”—soil moisture content. Not only has the model-predicted decline in Northern Hemispheric midlatitude soil moisture contents failed to materialize under the combined influence of many decades of rising atmospheric CO₂ concentrations and temperatures, it has become less of a threat, possibly as a consequence of biological impacts of the ongoing rise in the air's CO₂ content.

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1.3.9 Biological Processes

In a landmark paper published in *Global Change Biology*, Eastman *et al.* (2001) described the first comprehensive study of CO₂-induced regional climate change based on a hybrid atmosphere/vegetation model composed of linked meteorological and plant growth sub-models.

The authors of the groundbreaking study began by citing a number of peer-reviewed scientific research papers that demonstrated the likelihood of what they called “a crucial role for biospheric feedbacks on climate,” including processes driven by CO₂-induced changes in land surface albedo, leaf stomatal conductance, plant rooting profile, fractional coverage of the land by vegetation, plant roughness length and displacement height, vegetation phenology, time of planting and harvesting (in the case of agricultural crops), and plant growth. Next, they validated the model against real-world meteorological and plant growth data obtained for the 1989 growing season for the area located between approximately 35° and 48° N latitude and 96° and 110° W longitude. Last, they investigated how the climate of the region changes when (1) only the radiative effects of a doubling of the air’s CO₂ concentration are considered, (2) only the biological effects of a doubling of the air’s CO₂ concentration are considered, and (3) the radiative and biological effects of a doubling of the air’s CO₂ concentration occur simultaneously.

With respect to the area-averaged and seasonally averaged daily maximum air temperature, the radiative effects of a doubling of the atmospheric CO₂ concentration lead to a warming of only 0.014°C, and the biological effects of the extra CO₂ produced a cooling of fully 0.747°C. Considered together and including a nonlinear interaction term, the simultaneous radiative and biological effects of a doubling of the air’s CO₂ content thus produced a net cooling of 0.715°C.

With respect to the area-averaged and seasonally averaged daily minimum air temperature, the radiative effects of a doubling of the atmospheric CO₂ concentration led to a warming of 0.097°C, while the biological effects of the extra CO₂ produced a warming of 0.261°C. Considered together and again including the nonlinear interaction term, the simultaneous radiative and biological effects of a doubling of the air’s CO₂ content thus produced a net warming of 0.354°C.

During the day, then, when high air temperatures can be detrimental to both plant and animal life, the combined effect of the simultaneous radiative and biological impacts of an increase in the air’s CO₂ content acts to decrease daily maximum air temperature, alleviating potential heat stress. During the night, when low temperatures can be detrimental to plant and animal life, the combined effect of the radiative and biological impacts of an increase in the air’s CO₂ content acts to increase daily minimum air temperature, alleviating potential cold stress. When considering the day and night air temperature changes together, the mean daily air temperature range is reduced by approximately 1.069°C, leading to a more thermally stable environment, which in this case was also about 0.180°C cooler in the mean.

The authors also found the CO₂-induced change in area-averaged and seasonally averaged leaf area index was increased (+21.8%) with the simultaneous expression of the radiative and biological effects of a doubling of the air’s CO₂ content.

In summarizing their findings, the authors report “it is clear” the radiative effects of a doubling of the air’s CO₂ content have “little effect on anything” and play but a “minor role in the coupled biological and atmospheric system.” The authors acknowledge their analysis is “a regional-scale sensitivity study,” the results of which “cannot be linearly scaled up to global scales.”

Nevertheless the authors follow that caveat by noting their results “suggest that the regional response could be on the order of global climate sensitivities.”

Thus they conclude, “climate change that results from anthropogenic increases of CO₂ must consider the biological effects of enriched CO₂ as well as its radiative effect.” Most models exclude this important interaction.

In a paper published a decade later, Delire *et al.* (2011) used the CCMv3 and LMDz atmospheric GCMs and coupled these models to the latest versions of the Integrated Biosphere Simulator (IBIS) (Foley *et al.* 1996) and the ORCHIDEE biosphere model (Krinner *et al.* 2005), respectively. Each is a land surface model that includes plant characteristics such as the physiology of plant cover, plant phenology, carbon cycling, plant type competition, photosynthesis, and respiration. Both include daily and annual vegetation cycles and distinguish between trees and other types of vegetation (grasses, shrubs). Delire *et al.* ran each model with full capabilities and then by keeping the vegetation constant (fixed).

The GCM modeling strategy used by Delire *et al.* was to simulate the climate using observed sea surface temperatures from 1870–1899 available from the Hadley Centre in England. Their goal was to remove the impact of the ocean in order to highlight land-surface process differences in the coupled systems. The model was run for 400 years; the last 300 were used for analysis.

The interannual variability in plant cover generated by both models was similar to that of observed plant cover variability derived using satellite observations for 1982–1994. The LMDz-ORCHIDEE model showed stronger interannual variability, but in both the variability in tree cover was less than 5 percent, whereas for grasses it could be as much as 10 to 20 percent. Vegetation affected climate, as inferred by comparing the dynamic to fixed vegetation. The model strategy precluded comparison with observed climate.

The dynamic vegetation runs showed stronger low frequency variability than the fixed runs for both temperature and precipitation for each model system, but the disparity between the fixed and dynamic run was stronger for the CCMv3-IBIS system (Figure 1.3.9.1). The strength of the variability (0.05–2.0°C) compared favorably to that inferred by previous studies. The feedback between temperature and plant growth was generally positive (warmer temperatures, increased vegetation) in the mid-latitudes and poleward. The feedback was generally negative and weaker in semi-arid regions (increased vegetation, more evaporation, cooler temperatures). There was only a weak positive feedback in the precipitation

over most areas of the globe.

As we begin to understand more about the climate system, including the complexity of heat and mass exchange between various portions of it, we can more effectively model the past climate, including its variability. However, many of the climate simulations used to project future climate are fairly simple models that do not include a dynamic ocean or realistic representations of biological processes on land. These are problems that cannot continue to be ignored or overlooked. As Delire *et al.* indicate, “terrestrial ecosystems provide ‘memory’ to the climate system, causing important variations in the climate and ecological conditions on long-time-scales.”

Todd-Brown *et al.* (2013) point out, “because future climate projections depend on the carbon cycle, ESMs [Earth System Models] must be capable of accurately representing the pools and fluxes of carbon in the biosphere, particularly in soils that store a large fraction of terrestrial organic carbon,” but they note “there have been few quantitative assessments of ESM skill in predicting soil carbon stocks, contributing to uncertainty in model simulations.” “To help reduce this uncertainty,” as Todd-Brown *et al.* describe it, they “analyzed simulated soil carbon from ESMs participating in the Fifth Climate Model Intercomparison Project (CMIP5),” comparing the results from 11 model centers to empirical data obtained from the Harmonized World Soil Database (HWSD) and the Northern Circumpolar Soil Carbon Database (NCSCD). According to the seven scientists, some ESMs “simulated soil carbon stocks consistent with empirical estimates at the global and biome scales,” but all of the models “had difficulty representing soil carbon at the 1° scale.” They note, “despite similar overall structures, the models do not agree well among themselves or with empirical data on the global distribution of soil carbon.” Todd-Brown *et al.* conclude “all model structures may have serious shortcomings, since net primary productivity and temperature strongly influenced soil carbon stocks in ESMs but not in observational data.”

Todd-Brown *et al.* outline what may need to be done in order to resolve the failure of ESMs to adequately replicate the real world, including “better prediction of soil carbon drivers, more accurate model parameterization, and more comprehensive representation of critical biological and geochemical mechanisms in soil carbon sub-models.”

Climate Change Reconsidered II

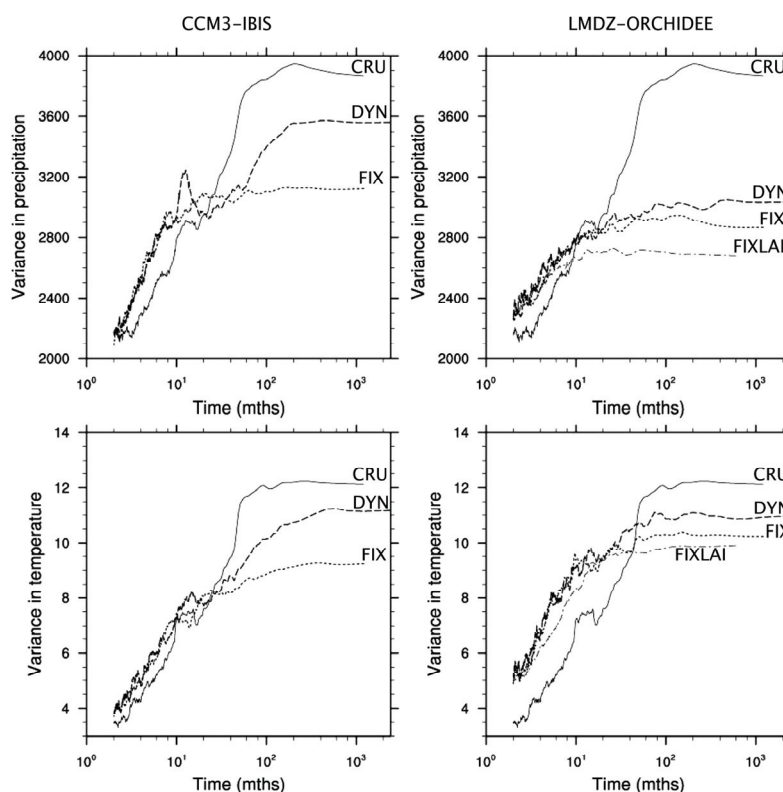


Figure 1.3.9.1. Power spectra of precipitation (top) and temperature (bottom) for the CCMv3-IBIS (left) and LMDz-ORCHIDEE (right) model systems. The solid line represents data from the Hadley Centre (observed), and the dashed (dotted) line represents dynamic [DYN] (fixed [FIX]) vegetation. Reprinted with permission from Delire, C., De Noblet-Ducoudre, N., Sima, A., and Gouriand, I. 2011. Vegetation dynamics enhancing long-term climate variability confirmed by two models. *Journal of Climate* **24**: 2238–2257.

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1.3.10 Permafrost

Almost all assessments of the potential impacts of climate change on the world's permafrost are based on a two-layer model that incorporates a seasonally frozen active layer and an underlying perennially frozen soil. Shur *et al.* (2005) examined the virtues of adding a transition zone layer to produce a more realistic three-layer model.

Through a review of the literature and theoretical and data analyses, Shur *et al.* showed, among other things, that the transition zone alternates between seasonally frozen ground and permafrost over sub-decadal to centennial time scales, functioning as a buffer between the active layer and the underlying perennial permafrost by increasing the latent heat required for thaw. Consequently, in the words of Shur *et al.*, use of a two-layer conceptual model in

permafrost studies “obscures effective understanding of the formation and properties of the upper permafrost and syngenetic permafrost, and makes a realistic determination of the stability of arctic geosystems under climatic fluctuations virtually impossible.” They conclude “the impacts of possible global warming in permafrost regions cannot be understood fully without consideration of a more realistic three-layer model.”

In light of the authors’ findings, it would appear two-layer model forecasts of future permafrost trends under various global warming scenarios are inadequate. And if the transition zone does indeed act as a buffer at sub-decadal to centennial time scales, then current permafrost trends are likely to be manifestations of past climatic trends, some of which may have taken place several decades ago or more.

Koven *et al.* (2013) note “permafrost is a critical component of high-latitude land and determines the character of the hydrology, ecology, and biogeochemistry of the region.” Therefore, they write, there is “widespread interest in the use of coupled atmosphere-ocean-land surface models to predict the fate of permafrost over the next centuries because (1) permafrost contains the largest organic carbon (C) reservoir in the terrestrial system (Tarnocai *et al.*, 2009), (2) permafrost stability is primarily dependent on temperature, and (3) global warming is expected to be relatively larger over the permafrost domain because of arctic amplification processes (Holland and Bitz, 2003).”

Koven *et al.* analyzed “output from a set of Earth system models (ESMs) that participated in phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2009) to evaluate the permafrost model predictions against observations and theoretical expectations and to compare the predicted fate of permafrost under warming scenarios.” The three U.S. researchers revealed “the models show a wide range of behaviors under the current climate, with many failing to agree with fundamental aspects of the observed soil thermal regime at high latitudes.”

Koven *et al.* report, “under future climate change, the models differ in their degree of warming, both globally and at high latitudes, and also in the response of permafrost to this warming.” They note “there is a wide range of possible magnitudes in their responses, from 6% to 29% permafrost loss per 1°C high-latitude warming.” Several of the models, they report, “predict substantial permafrost degradation has already occurred (ranging from 3% gain to 49% loss relative to 1850 conditions)” and “the majority of

models at the high end of relative twentieth-century permafrost loss also show unrealistically small preindustrial permafrost extent.” They also note “there is wide model disagreement on the value of the difference in mean temperature across the air-soil interface, with several of the models [even] predicting the wrong sign for this statistic” and “there is wide model disagreement in the changes of [the] mean and [the] amplitude of soil temperatures with depth.”

Koven *et al.* conclude by stating, “with this analysis, we show that widespread disagreement exists among this generation of ESMs,” once again suggesting current Earth system models are not yet accurate enough for real-world application.

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1.3.11 Miscellaneous

Several other studies have documented inadequacies in climate model projections. This subsection highlights those that do not quite fit in other subsections of Section 1.4 or that deal with multiple climatic elements and, as such, are best suited for this miscellaneous category.

“Climate variability,” in the words of Latif and Keenlyside (2011), “can be either generated internally by interactions within or between the individual climate subcomponents (e.g., atmosphere, ocean and

sea ice) or externally by e.g., volcanic eruptions, variations in the solar insolation at the top of the atmosphere, or changed atmospheric greenhouse gas concentrations in response to anthropogenic emissions.” Some examples of these internal variations are “the North Atlantic Oscillation (NAO), the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Variability (PDV), and the Atlantic Multidecadal Variability (AMV),” all of which “project on global or hemispheric surface air temperature (SAT), thereby masking anthropogenic climate change.”

In a review of this complex subject, Latif and Keenlyside—who hold positions at Germany’s Leibniz-Institute for Meereswissenschaften at the University of Kiel—first describe various mechanisms responsible for internal variability, giving special attention to the variability of the Atlantic Meridional Overturning Circulation (AMOC), which they suggest is likely the origin of a considerable part of the decadal variability within the Atlantic Sector, after which they discuss the challenge of decadal SAT predictability and various factors limiting its realization.

The two researchers identify numerous problems that hamper decadal climate predictability, including that “the models suffer from large biases.” In the cases of annual mean sea surface temperature (SST) and SAT over land, for example, they state “typical errors can amount up to 10°C in certain regions,” as Randall *et al.* (2007) found to be the case for many of the IPCC-AR4 models. Latif and Keenlyside also note several models “fail to simulate a realistic El Niño/Southern Oscillation.” In addition, the researchers point out “several assumptions have generally to be made about the process under consideration that cannot be rigorously justified, and this is a major source of uncertainty.”

Another problem they discuss is that “some components of the climate system are not well represented or not at all part of standard climate models,” one example being the models’ neglect of the stratosphere. This omission is serious; Latif and Keenlyside say “recent studies indicate that the mid-latitude response to both tropical and extra-tropical SST anomalies over the North Atlantic Sector may critically depend on stratospheric feedbacks,” noting Ineson and Scaife (2009) present evidence for “an active stratospheric role in the transition to cold conditions in northern Europe and mild conditions in southern Europe in late winter during El Niño years.”

An additional common model shortcoming, even

in standalone integrations with models forced by observed SSTs, is that model simulations of rainfall in the Sahel “fail to reproduce the correct magnitude of the decadal precipitation anomalies.” Still another failure, as shown by Stroeve *et al.* (2007), is that “virtually all climate models considerably underestimate the observed Arctic sea ice decline during the recent decades in the so-called 20th century integrations with prescribed (known natural and anthropogenic) observed forcing.” In addition, “atmospheric chemistry and aerosol processes are still not well incorporated into current climate models.”

In summing up their findings, which include those noted above and many more, Latif and Keenlyside state, “a sufficient understanding of the mechanisms of decadal-to-multidecadal variability is lacking.” They note “state-of-the-art climate models suffer from large biases” and “are incomplete and do not incorporate potentially important physics.” Various mechanisms “differ strongly from model to model,” they point out; “the poor observational database does not allow a distinction between ‘realistic’ and ‘unrealistic’ simulations”; and many models “still fail to simulate a realistic El Niño/Southern Oscillation.” Therefore, they conclude, “it cannot be assumed that current climate models are well suited to realize the full decadal predictability potential”—a somewhat obscure way of stating current state-of-the-art climate models are not good enough to make reasonably accurate simulations of climate change over a period of time (either in the past or the future) that is measured in mere decades.

In another paper, Lucarini *et al.* (2007) compared for the period 1962–2000 “the estimate of the northern hemisphere mid-latitude winter atmospheric variability within the available 20th century simulations of 19 global climate models included in the Intergovernmental Panel on Climate Change [IPCC] 4th Assessment Report” with “the NCEP-NCAR and ECMWF reanalyses,” compilations of real-world observations produced by the National Center for Environmental Prediction (NCEP), in collaboration with the National Center for Atmospheric Research (NCAR), and by the European Center for Mid-Range Weather Forecast (ECMWF). The five Italian researchers report “large biases, in several cases larger than 20%, are found in all the considered metrics between the wave climatologies of most IPCC models and the reanalyses, while the span of the climatologies of the various models is, in all cases, around 50%.” They also report “the traveling baroclinic waves are typically overestimated by the

climate models, while the planetary waves are usually underestimated,” and “the model results do not cluster around their ensemble mean.” The authors conclude by stating, “this study suggests caveats with respect to the ability of most of the presently available climate models in representing the statistical properties of the global scale atmospheric dynamics of the present climate and, *a fortiori* [“all the more,” as per Webster’s Dictionary], in the perspective of modeling climate change.”

According to Scherrer (2011), “climate model verification primarily focused [in the past] on the representation of climatological means.” But “on the other hand,” he continues, “a good representation of second-order moments (i.e., variability) on different time scales (e.g., daily, month-to-month, or interannual, etc.) is crucial and probably provides an even better test as to whether [real-world] physical processes are well represented in the models.” Working with twentieth century climate model runs prepared within the context of the IPCC AR4 assessment (now called the CMIP3 data set), Scherrer set out to compare model simulations of the interannual variability (IAV) of 2-m-height air temperature (*T*), sea level pressure (*SLP*), and precipitation (*P*) over the twentieth century with observational and reanalysis data sets for the same time period using standard deviation-based variability indices.

The Swiss scientist describes a number of problems he encountered with the CMIP3 models. With respect to *SLP*, the situation was pretty good: “only minor IAV problems are found.” With respect to temperature, however, differences between observations and models are, in general, “larger than those for *SLP*.” And for precipitation, “IAV is ‘all over the place’ and no clear relations with *T* and *SLP* IAV problems can be established.”

Concentrating thereafter mostly on temperature, Scherrer notes “a few models represent *T* IAV much worse than others and create spurious relations of IAV representation and the climate change signal.” Among the “better” IAV models, he finds “the ‘good’ IAV models in the tropics are in general not also the ‘good’ IAV models in the extra-tropics,” and “the ‘good’ IAV models over the sea are in general not the ‘good’ IAV models over land.” He further notes “similar results are found for the relation between *T* IAV representation and the amplitude of projected changes in temperature.”

“In general,” Scherrer writes, “it is concluded that, aggregated over very large regions, hardly any

robust relations exist between the models’ ability to correctly represent IAV and the projected temperature change.” He says these results represent “a plea to remove the ‘obviously wrong’ models (e.g., like those that have sea ice extending to below 50°N in the Atlantic and DJF temperature biases of ~40°C in Iceland, cf. Raisanen, 2007) before doing climate analyses.”

de Boer *et al.* (2012) point out “observed and projected changes in the Arctic region are some of the most striking concerns surrounding climate trends,” noting the latter “likely have important consequences both within the Arctic and globally.” They further note “a new generation of Earth system models has been utilized to prepare climate projections for the fifth phase of the Coupled Model Intercomparison Project (CMIP5),” the results of which are planned to be used “in the Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report* (AR5).” They set out to determine how well these models perform, but the closest they could come to conducting such a test was to interrogate the models used in the AR4 report of the IPCC. Thus, de Boer *et al.* simulated key features of the Arctic atmosphere in the Community Climate System Model, version 4 (CCSM4) and compared the results of those simulations “against observational and reanalysis datasets for the present-day (1981–2005).”

Describing problems they encountered in this endeavor, the seven scientists report “simulated surface air temperatures are found to be slightly too cold,” “evaluation of the sea level pressure [*SLP*] demonstrates some large biases, most noticeably an under simulation of the Beaufort High during spring and autumn,” “monthly Arctic-wide [*SLP*] biases of up to 13 mb are reported,” “cloud cover is under-predicted for all but summer months,” and “cloud phase is demonstrated to be different from observations.” They also found “simulated all-sky liquid water paths are too high,” “ice water path was generally too low,” and “precipitation is found to be excessive over much of the Arctic compared to ERA-40 and the Global Precipitation Climatology Project estimates.” They report “biases of 40%-150% are calculated over northern North America, northern Greenland, and the Arctic Ocean,” while “over the Norwegian Sea ... evaporation is over-simulated by up to 3.5 mm/day,” such that “P-E is generally too high over much of the Arctic, particularly over coastal Greenland.”

de Boer *et al.* also found “CCSM4 over-predicts surface energy fluxes during summer months” and

“under-predicts it during winter.” They also report “the strengths of surface inversions were found to be too great in CCSM4 when compared to ERA-40, with distributions showing a near-doubling of strength,” and (15) “CCSM4 is found to have more inversions than ERA-40 for all months.”

Oddly, de Boer *et al.* conclude “CCSM4 provides a consistent representation of present-day Arctic climate” and “in doing so it represents individual components of the Arctic atmosphere with respectable accuracy.” This statement seems to us to be an egregious misuse of the word “respectable.”

Blazquez and Nuñez (2013) point out “the first step to understand climate changes that are likely to occur in the future is the assessment of the present climate,” which “allows determining the model deficiencies.” The two authors set out to “[evaluate] a present climate simulation over southern South America performed with the Meteorological Research Institute/Japanese Meteorological Agency (MRI/JMA) high resolution global model.”

Comparing their simulated wind results with data from the European Centre Medium Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA 40), and their temperature and precipitation simulations with data from various meteorological stations, the two Argentinian researchers report discovering significant model deficiencies: Speeds of the low level jet and the westerlies “are generally underestimated” and at upper levels “the westerlies are overestimated over central Argentina.” During December-February, March-May, and September-November, they report, “the MRI/JMA global model underestimates the temperature over east of Argentina, west of Uruguay, south of Chile and over tropical latitudes” and “overestimates are observed over central Argentina,” while “in June-August the model underestimates the temperature over most of Argentina, south of Chile and to the north of 20°S.” They also found “the model overestimates temperature interannual variability in all regions and all seasons, except in [June-July-August].”

With respect to precipitation, the authors found in all seasons the model yields “an underestimation of the precipitation in the southeast of Brazil and south of Peru and an overestimation in Bolivia, Uruguay, north and central Chile and north of Peru,” and during “the dry season (JJA) the model greatly overestimates the precipitation over northeastern and central Argentina.” They note “in regions located over mountainous areas the model presents a poor reproduction of the annual cycle” and “observed

precipitation trends are generally positive whereas simulated ones are negative.”

Landrum *et al.* (2013) compared Last Millennium (LM) simulations of the Community Climate System Model, version 4 (CCSM4) to real-world “data reconstructions of temperature, the hydrologic cycle, and modes of climate variability.” In addition to some successes of the CCSM4, the seven scientists report a number of failures. They note “the LM simulation does not reproduce La Niña-like cooling in the eastern Pacific Ocean during the MCA [Medieval Climate Anomaly] relative to the LIA [Little Ice Age], as has been suggested by proxy reconstructions,” and “patterns of simulated precipitation change for the Asian monsoon to large volcanic eruptions have nearly opposite anomalies from those reconstructed from tree-ring chronologies.” They report CCSM4 “does not simulate a persistent positive NAO [North Atlantic Oscillation] or a prolonged period of negative PDO [Pacific Decadal Oscillation] during the MCA, as suggested by some proxy reconstructions” and “the model simulates cooling of ~1.0°-1.5°C after the large eruptions of the late thirteenth, mid-fifteenth, late eighteenth, and early nineteenth centuries, 2-3 times larger than the NH [Northern Hemisphere] summer anomalies estimated from tree-ring or multiproxy reconstructions.” They further report “twentieth-century simulations indicate that the CCSM4 hemispheric response to volcanic eruptions is stronger than observed (Meehl *et al.*, 2012)” and they “do not find a persistent positive NAO or a prolonged period of negative PDO during the MCA suggested by the proxy reconstructions (MacDonald and Case, 2005; Trouet *et al.*, 2009).”

Su *et al.* (2013) evaluated “the performance of 24 GCMs available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) ... over the eastern Tibetan Plateau (TP) by comparing the model outputs with ground observations for the period 1961–2005,” focusing their attention on temperature and precipitation. The five researchers report that with respect to temperature, “most GCMs reasonably capture the climatological patterns and spatial variations of the observed climate,” but “the majority of the models have cold biases, with a mean underestimation of 1.1°-2.5°C for the months December-May, and less than 1°C for June-October.” As for precipitation, they state “the simulations of all models overestimate the observations in climatological annual means by 62.0%-183.0%,” while noting “only half of the 24 GCMs are able to

reproduce the observed seasonal pattern,” including “the sharp contrast between dry winters and wet summers.” The last of these observations clearly suggests, as Su *et al.* note, that there is “a critical need to improve precipitation-related processes in these models.” They found 90-year forward projections of both precipitation and temperature “differ much more among various models than among emissions scenarios,” suggesting temperature-related processes in the models must be improved upon as well.

In a paper published in *Nature Climate Change*, Knutti and Sedlacek (2013) write “estimates of impacts from anthropogenic climate change rely on projections from climate models,” but “uncertainties in those have often been a limiting factor, particularly on local scales.” They note “a new generation of more complex models running scenarios for the upcoming Intergovernmental Panel on Climate Change *Fifth Assessment Report* (IPCC AR5) is widely, and perhaps naively, expected to provide more detailed and more certain projections.”

Exploring whether these expectations are being met, the two researchers performed “a first comparison between projections from CMIP3 and CMIP5,” in order to see to what extent real progress in the modeling of Earth’s global climate may have been made. Knutti and Sedlacek report “projected global temperature change from the new models is remarkably similar to that from those used in IPCC AR4 after accounting for the different underlying scenarios” and “the local model spread has not changed much despite substantial model development and a massive increase in computational capacity.” They write “there is ... little evidence from CMIP5 that our ability to constrain the large-scale climate feedbacks has improved significantly”; “model mean patterns of temperature and precipitation change ... are remarkably similar in CMIP3 and CMIP5”; and “robustness over land is slightly higher but also similar in CMIP3 and CMIP5,” which they describe as “troublesome.”

In light of these findings, and “if the past is a guide to the future,” as the two researchers put it, “then uncertainties in climate change are unlikely to decrease quickly, and may even grow temporarily.” The scientists say they “have illustrated this for seasonal temperature and precipitation” and “it is likely that impact-relevant predictions, for example of extreme weather events, may be even harder to improve.”

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1.4 Large Scale Phenomena and Teleconnections

The role of irregular interannual and interdecadal climate variations in forcing climate change is now being quantified by climate science. Some specific variations—the Pacific Decadal Oscillation (PDO), for example—have been identified and evaluated, and they correlate well with decadal changes in global temperatures throughout the twentieth century. Other variations—such as the El Niño and Southern Oscillation (ENSO)—have been recognized for decades.

Although scientists can explain the role of these circulations in local climate variability and understand their dynamic evolution, the trigger mechanisms for initiating changes in these oscillations are not well understood. We use climate models to improve our understanding of them. A model, however, cannot replicate the basic flow adequately. A by-product of this failure is that model output can have significant biases, a problem weather forecasters have recognized for decades.

This section examines several of these features of Earth’s climate and how well they are simulated by the models. Many such studies are highlighted in the subsections below; many more were addressed in earlier sections of this chapter, including the sections on oceans, temperature, and precipitation.

1.4.1 El Niño/Southern Oscillation

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (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. This

section highlights findings that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality, beginning with several studies that described the status of the problem a decade ago.

In a comparison of 24 coupled ocean-atmosphere climate models, Latif *et al.* (2001) report, “almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology.” They also note, “only a few of the coupled models simulate the El Niño/Southern Oscillation in terms of gross equatorial SST anomalies realistically.” And they state, “no model has been found that simulates realistically all aspects of the interannual SST variability.” Consequently, because “changes in sea surface temperature are both the cause and consequence of wind fluctuations,” according to Fedorov and Philander (2000), and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising the researchers conclude climate models near the turn of the century did not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also played a role in those models’ failure to simulate ENSO. According to Overpeck and Webb (2000), there was evidence that “ENSO may change in ways that we do not yet understand,” and these “ways” clearly had not yet been modeled. White *et al.* (2001), for example, found “global warming and cooling during Earth’s internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance”; they note these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) made a case for a lunar forcing of ENSO activity, a factor not included in any climate model of that time.

Another example of the inability of the most sophisticated of late twentieth century climate models to properly describe El Niño events was provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997–98 El Niño. They found the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from zero to eight months. They also determined no models were able to anticipate even one-half of the actual amplitude of the El Niño’s peak at a medium-range

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lead time of six to 11 months. Hence, they state, “since no models were able to provide useful predictions at the medium and long ranges, there were no models that provided both useful and skillful forecasts for the entirety of the 1997–98 El Niño.”

It is little wonder several scientists criticized model simulations of ENSO behavior at the turn of the century, including Walsh and Pittock (1998), who conclude, “there is insufficient confidence in the predictions of current models regarding any changes in ENSO” and Fedorov and Philander (2000), who wrote, “at this time, it is impossible to decide which, if any, are correct.”

The rest of this section considers whether the situation has improved over the past decade.

Huber and Caballero (2003) introduce their contribution to the subject by stating, “studies of future transient global warming with coupled ocean-atmosphere models find a shift to a more El Niño-like state,” although they also report the “permanent El Niño state”—which has been hypothesized by some in the climate community—“is by no means uniformly predicted by a majority of models.” To help resolve this battle of the models, they worked with still another model plus real-world data pertaining to the Eocene, the past geologic epoch—much warmer than the recent past—which provided, in their words, “a particularly exacting test of the robustness of ENSO.” They used the Community Climate System Model of the National Center for Atmospheric Research, which they state yielded “a faithful reproduction of modern-day ENSO variability,” to “simulate the Eocene climate and determine whether the model predicts significant ENSO variability.” In addition, they compared the model results against middle Eocene lake-sediment records from the Lake Gosiute complex in Wyoming and Eckfield Maar in Germany.

Huber and Caballero report the model simulations showed “little change in ... ENSO, in agreement with proxies.” They also note other studies “indicate an ENSO shutdown as recently as ~6000 years ago, a period only slightly warmer than the present.” They conclude “this result contrasts with theories linking past and future ‘hothouse’ climates with a shift toward a permanent El Niño-like state.”

Three years later, Joseph and Nigam (2006) evaluated several climate models “by examining the extent to which they simulated key features of the leading mode of interannual climate variability: El Niño-Southern Oscillation (ENSO), which they describe as “a dominant pattern of ocean-atmosphere

variability with substantial global climate impact,” based on “the Intergovernmental Panel on Climate Change’s (IPCC) *Fourth Assessment Report* (AR4) simulations of twentieth-century climate.” Different models were found to do well in some respects but not so well in others. For example, they found climate models “are still unable to simulate many features of ENSO variability and its circulation and hydroclimate teleconnections.” They found the models had only “begun to make inroads in simulating key features of ENSO variability.”

The two scientists say their study suggests “climate system models are not quite ready for making projections of regional-to-continental scale hydroclimate variability and change” and “predicting regional climate variability/change remains an onerous burden on models.”

One year later, L’Ecuyer and Stephens (2007) asked how well state-of-the-art climate models reproduced the workings of real-world energy and water cycles, noting “our ability to model the climate system and its response to natural and anthropogenic forcings requires a faithful representation of the complex interactions that exist between radiation, clouds, and precipitation and their influence on the large-scale energy balance and heat transport in the atmosphere,” further stating “it is also critical to assess [model] response to shorter-term natural variability in environmental forcings using observations.”

The two researchers used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period January 1998 through December 1999 in order to evaluate the sensitivity of atmospheric heating (and the factors that modify it) to changes in east-west SST gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere utilized in the IPCC’s AR4. This protocol, in their words, “provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures.”

L’Ecuyer and Stephens report “a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event.” They also discovered “the intermodel variability in the responses of

precipitation, total heating, and vertical motion [was] often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO.” In addition, they found “many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds.” In light of these much-less-than-adequate findings, they conclude, “deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models,” further stating these deficiencies “cannot be ignored when interpreting their predictions of future climate.”

Paeth *et al.* (2008) compared 79 coupled ocean-atmosphere climate simulations derived from 12 different state-of-the-art climate models forced by six IPCC emission scenarios with observational data in order to evaluate how well they reproduced the spatio-temporal characteristics of ENSO over the twentieth century, after which they compared the various models’ twenty-first century simulations of ENSO and the Indian and West African monsoons to one another.

With respect to the twentieth century, this work revealed “all considered climate models draw a reasonable picture of the key features of ENSO.” With respect to the twenty-first century, on the other hand, they note “the differences between the models are stronger than between the emission scenarios,” while “the atmospheric component of ENSO and the West African monsoon are barely affected.” Their “overall conclusion” is that “we still cannot say much about the future behavior of tropical climate.” They consider their study to be merely “a benchmark for further investigations with more recent models in order to document a gain in knowledge or stagnation over the past five years.”

Jin *et al.* (2008) investigated the overall skill of ENSO prediction in retrospective forecasts made with ten different state-of-the-art ocean-atmosphere coupled general circulation models with respect to their ability to hindcast real-world observations for the 22 years from 1980 to 2001. They found almost all models have problems simulating the mean equatorial SST and its annual cycle. They write, “none of the models we examined attain good performance in simulating the mean annual cycle of SST, even with the advantage of starting from realistic initial conditions.” They also note, “with

increasing lead time, this discrepancy gets worse” and “the phase and peak amplitude of westward propagation of the annual cycle in the eastern and central equatorial Pacific are different from those observed.” They also found “ENSO-neutral years are far worse predicted than growing warm and cold events” and “the skill of forecasts that start in February or May drops faster than that of forecasts that start in August or November.” They and others call this behavior “the spring predictability barrier.” Jin *et al.* conclude, “accurately predicting the strength and timing of ENSO events continues to be a critical challenge for dynamical models of all levels of complexity.”

McLean *et al.* (2009) quantified “the effect of possible ENSO forcing on mean global temperature, both short-term and long-term,” using Southern Oscillation Index (SOI) data provided by the Australian government’s Bureau of Meteorology. This parameter was defined as “the standardized anomaly of the seasonal mean sea level pressure difference between Tahiti and Darwin, divided by the standard deviation of the difference and multiplied by 10.” The temperature data employed in this endeavor were “the University of Alabama in Huntsville lower-tropospheric (LT) temperature data based on measurements from selected view angles of Microwave Sounding Unit (MSU) channel LT 2” for the period December 1979 to June 2008, supplemented by “balloon-based instrumentation (radiosondes).” For the latter data, dating back to 1958, they employed the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) product (A) of the U.S. National Climatic Data Center, which represents the atmospheric layer between approximately 1,500 and 9,000 meters altitude.

McLean *et al.* found “change in SOI accounts for 72% of the variance in GTTA [Global Tropospheric Temperature Anomalies] for the 29-year-long MSU record and 68% of the variance in GTTA for the longer 50-year RATPAC record,” as well as “81% of the variance in tropospheric temperature anomalies in the tropics,” where they note ENSO “is known to exercise a particularly strong influence.” In addition, they determined “shifts in temperature are consistent with shifts in the SOI that occur about 7 months earlier.” The three researchers conclude, “natural climate forcing associated with ENSO is a major contributor to variability and perhaps recent trends in global temperature, a relationship that is not included in current global climate models.”

Harmonic analysis is useful in this discussion because it can be used to construct models of time series or spatial patterns. It also can be used as a diagnostic tool on the same type of data sets. Harmonics are natural solutions to differential equations that represent the motion in oscillating systems and take the form of waves, usually represented as trigonometric functions (for example sine or cosine). Harmonics simply represent the transformation of data from Cartesian coordinates (space and/or time) to a wave coordinate. Thus, “wave-like” phenomena not readily apparent to the eye, or which appear as random noise, can be identified in a data set.

The El Niño (warm East Pacific tropical water temperatures)/La Niña (cold East Pacific tropical water temperatures) phenomenon is known to occur in a quasi-cyclic fashion repeating every two to seven years. It is the leading reason for the global variation in temperatures and precipitation on an interannual time scale. Conceptual models and general circulation models (GCMs) have been used to hypothesize that El Niño may arise as a result of internal nonlinear processes.

White and Liu (2008) found El Niño/La Niña pairs may be “phase locked” to the quasi-decadal oscillation (QDO), which is linked to the 11-year solar cycle. Phase locking means two different harmonics vary in the same way with respect to each other. The simplest example of this is pure “constructive” or “destructive” interference. The authors performed harmonic analysis on a time series of Pacific region sea surface temperatures (SSTs) for 1895–2005. They also gathered 110 years of data from a multi-century run of a coupled atmosphere-ocean GCM corresponding to the observations.

The authors found an 11-year QDO cycle in the observed record as well as strong peaks in the years associated with El Niño, especially at 3.6 and 2.2 years. When the authors ran the GCM without the 11-year solar forcing, the computer model could not reproduce the QDO in its SST record. When the GCM included the forcing, the model not only reproduced the QDO but also the strong peaks in the 3.6 and 2.2 year period similar to observations.

White and Liu also found a “phase locking” of the 11-year cycle with the 3.6 and 2.2 year cycles in both the model and the observations. This suggests the higher frequency oscillations had higher amplitudes in step with the lower frequency one and are “hitting” a maximum (minimum) roughly in correspondence with the low frequency cycle.

White and Liu went further with their analysis, taking the nine 11 year cycles found in each record and “compositing” them (Figure 1.4.1.1). In both the model and observations, similar behavior was observed. When the 11, 3.6, and 2.2 (ridge—warm—El Niño / trough—cold—La Niña) year cycles were added together and superimposed on the 11-year cycle as a visual aid, it was apparent El Niño/La Niña couplets occurred together on the ascending and descending side of the QDO, but that a strong El Niño (La Niña) also can occur at the peak (in the valley) of the QDO.

Finally, White and Liu used the previously derived QDO model of Jin (1997) and incorporated their findings, finding a pattern similar to that shown in Figure 1.4.1.1. They also used the 3.6 and 2.2 year harmonics to compare to the observed record with the 11-year cycle filtered out. They found this combination reliably identified 26 of 32 El Niño events of 1895–2005.

The authors therefore provide convincing evidence the 11-year solar cycle may be the trigger for El Niño/La Niña events. By using harmonic analysis on observed and model data, they found similar El Niño-related behavior in each, meaning “the solar forced QDO forces the ~3.6 year ENSO signal; which in turn forces the ~2.2 year ENSO signal, and so on.” There are two important results to take away from this work: Models that include solar forcing have become more proficient at capturing interannual variability, and El Niño and La Niña onsets may be somewhat predictable even 10 years in advance. Such developments would be a boon for long-range forecasting.

In a review paper two years later, Vecchi and Wittenberg (2010) “[explored] our current understanding of these issues,” stating it is “of great interest to understand the character of past and future ENSO variations.” The two researchers at the U.S. National Oceanic and Atmospheric Administration’s Geophysical Fluid Dynamics Laboratory point out “the amplitude and character of ENSO have been observed to exhibit substantial variations on timescales of decades to centuries” and “many of these changes over the past millennium resemble those that arise from internally generated climate variations in an unforced climate model.” In addition, they report “ENSO activity and characteristics have been found to depend on the state of the tropical Pacific climate system, which is expected to change in the 21st century in response to changes in radiative forcing and internal climate variability.” The two

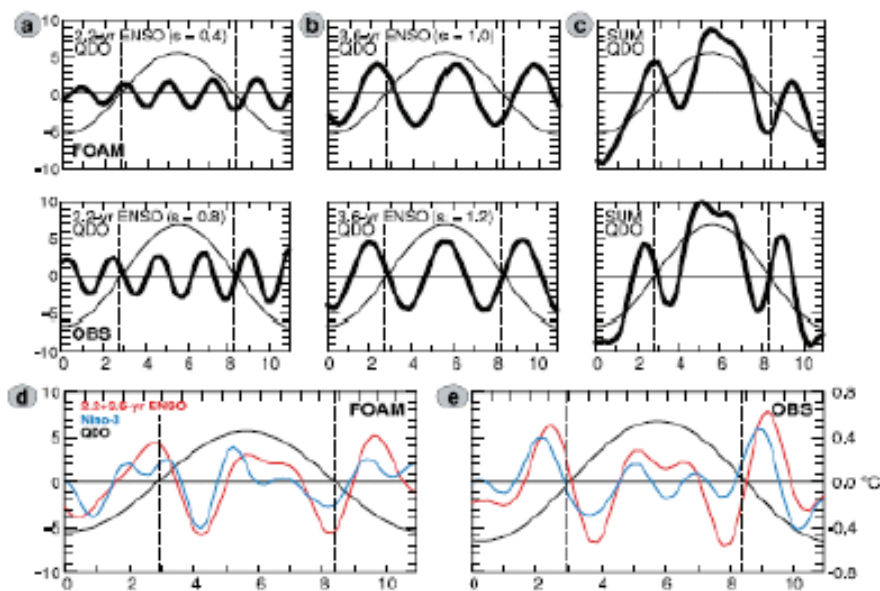


Figure 1.4.1.1. The nine member composites of each 11-year QDO cycle for the observations (obs) and the GCM (FOAM): (a) is the QDO (thin) and 2.2 year El Niño (thick), (b) is the same as (a) except for the 3.6 year cycle, and (c) is the sum of the three cycles (thick) shown against the 11 year cycle (thin). For (d) and (e) the figure shows the sum of the 2.2 and 3.6 year cycle against the entire record and the 11 year cycle for the (d) model, and (e) observations. Reprinted with permission from White, W.B. and Liu, Z. 2008. Non-linear alignment of El Niño to the 11-yr solar cycle. *Geophysical Research Letters*, **35**, L19607, doi:10.1029/2008GL034831.

scientists also note “the extent and character of the response of ENSO to increases in greenhouse gases are still a topic of considerable research” and “given the results published to date, we cannot yet rule out possibilities of an increase, decrease, or no change in ENSO activity arising from increases in CO₂.”

Vecchi and Wittenberg conclude their review of the subject by stating “we expect the climate system to keep exhibiting large-scale internal variations,” but they add, “the ENSO variations we see in decades to come may be different than those seen in recent decades.” They admit “we are not currently at a state to confidently project what those changes will be.”

Catto *et al.* (2012a) write “the El Niño-Southern Oscillation (ENSO) is linked to the interannual climate variability of Australia, in part through its effect on the sea surface temperatures (SSTs) around northern Australia,” as has been documented by Hendon (2003) and Catto *et al.* (2012b). They explain “it is important that global coupled climate models are able to represent this link between ENSO and north Australian SSTs so that we can have more confidence in the projections of future climate change

for the Australian region.” For the authors’ contribution to the topic, “the link between ENSO and north Australian SSTs has been evaluated in the models participating in CMIP5 with a view to comparing them with the CMIP3 models evaluated in Catto *et al.* (2012b).”

The three Australian researchers’ study revealed “the CMIP5 models still show a wide range in their ability to represent both ENSO events themselves, and their relationship to north Australian SST”; “most of the models fail to capture the strong seasonal cycle of correlation between the Niño-3.4 and north Australian SSTs”; and “the models in general are still missing some underlying process or mechanism.” Catto *et al.* conclude, “gaining a deeper understanding of the physical mechanism behind the strong link between the SSTs in the Niño-3.4 region and to

the north of Australia using these models” is “a vital next step” for this work, which they state is required “to elucidate the processes missing from the models that cannot capture the link.”

Zhang and Jin (2012) indicate “ENSO behaviors in coupled models have been widely evaluated,” citing Neelin *et al.* (1992), Delecluse *et al.* (1998), Latif *et al.* (2001), Davey *et al.* (2002), AchuataRao and Sperber (2002, 2006), Capotondi *et al.* (2006), Guilyardi (2006), and Zhang *et al.* (2010). However, they write, “coupled models still exhibit large biases in modeling the basic features of ENSO,” citing Guilyardi *et al.* (2009). Among these biases is “a sea surface temperature (SST) anomaly (SSTA) too tightly confined to the equator (e.g., Stockdale *et al.*, 1998; Kang *et al.*, 2001).” More specifically, and recently, they say, “it was shown that the ENSO meridional width in the models participating in Phase 3 of the Coupled Model Inter-comparison Project (CMIP3) is only about two thirds of what is observed,” citing Zhang *et al.* (2012).

Zhang and Jin ask the obvious question: “Does the systematic narrow bias in ENSO width still exist

in current models developed for Phase 5 of the CMIP (CMIP5)?” They answer the question by assessing the ENSO meridional widths simulated by 15 CMIP5 models and 15 CMIP3 models for the period 1900–1999, comparing the results of both groups against observation-based monthly SST data from the Hadley Center Sea Ice and Sea Surface Temperature (HadISST) data of Rayner *et al.* (2003). The analysis indicated “a systematic narrow bias in ENSO meridional width remains in the CMIP5 models,” although they state the newest results represent “a modest improvement over previous models.” Is a modest improvement good enough? That question remains to be answered.

Roxy *et al.* (2013) point out recent studies have highlighted the existence of a new phenomenon, referred to as the El Niño Modoki, characterized by a warm sea surface temperature (SST) anomaly in the central equatorial Pacific and a cold SST anomaly in the western and eastern Pacific. Some observers of this phenomenon have argued “the increasing frequency of the El Niño Modoki in recent decades is due to global warming.” Roxy *et al.*, considering it imperative to examine the changing teleconnection between ENSO/Modoki and the Indian summer monsoon, revisited “climate change experiments under the fourth *Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC), namely the twentieth century simulations (20C3M) and Special Report on Emissions Scenarios (SRES) A1B, ... to study whether these models can reproduce the ENSO and ENSO Modoki patterns” and “their teleconnections with the Indian summer monsoon, and also the implications for the future.”

The four researchers from India report “only ~1/4th of the models from 20C3M capture either ENSO or ENSO Modoki patterns in June, July, August and September.” They note “of this 1/4th, only two models simulate both ENSO and ENSO Modoki patterns as important modes” and “of these two, only one model simulates both ENSO and ENSO Modoki as important modes during both summer and winter.” In addition, they note the two models that demonstrate ENSO Modoki, as well as ENSO associated variance in both 20C3M and SRES A1B, project the *opposite* types of impacts of SRES A1B.

Roxy *et al.* say their findings are indicative of “the challenges associated with the limitations of the models in reproducing the variability of the monsoons and ENSO flavors, not to speak of failing in capturing the potential impacts of global warming as they are expected to.”

Koumoutsaris (2013) reports, “currently, global climate models disagree in their estimates of feedbacks, and this is one of the main reasons for uncertainty in future climate projections,” citing Bony *et al.* (2006). He further notes “in order to unveil the origin of these inter-model differences, model simulations need to be evaluated against observations of present climate.” He estimated “the feedbacks from water vapor, lapse-rate, Planck, surface albedo and clouds, using models and observations based on the climate response over the last 30 years,” short-term feedbacks that “result both from external changes in the forcing (due to greenhouse gas increases, volcanic and industrial aerosol emissions) and internal climate variations (mostly due to ENSO variability).” The Swiss scientist reports “the CMIP3 models show a much larger interdecile range for all short-term feedbacks in comparison to the long-term ones,” which he states “is also the case for the three models with the most realistic ENSO representation,” citing van Oldenborgh *et al.* (2005). He also indicates the models have difficulty capturing “the position and magnitude of ENSO teleconnection patterns.” In addition, he reports “the uncertainty in the cloud feedback, using a combination of reanalysis and satellite data, is still very large.”

Koumoutsaris concludes his analyses indicate “important aspects of the ENSO variability are still poorly understood and/or simulated.” Regarding cloud feedback, he says it is difficult to come to “any firm conclusion,” even as to the sign of the feedback.” Clearly there remain multiple problems in the ability of models to reliably simulate various aspects of climate associated with ENSO events, casting further doubt on the overall ability of models to simulate the future climate of the planet in general.

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1.4.2 Atlantic and Pacific Ocean Multidecadal Variability (AMV)

The study of Semenov *et al.* (2010) shows natural variability contributed significantly to the warming period in the last few decades of the twentieth century and even may be responsible for the majority of the warming. The work of Petoukhov and Semenov (2010) has been cited as evidence that cold winters would be consistent with anthropogenic global warming. The reasoning follows this path: global warming in the Arctic would leave less sea ice, and

with less sea ice, more heat is released to the air. As a result, continents could be colder since more moisture-laden air can mean more clouds and more snow, and thus colder temperatures over land. This is called the “Warm Arctic-Cold Continents” conjecture.

Semenov *et al.* (2010) first examined the results of several different model experiments performed by others, finding “North Atlantic sea surface temperature changes do project onto Northern Hemisphere and global surface air temperatures in these models,” especially as these relate to the warming of the early twentieth century. They used the ECHAM5 model (European Centre for Medium Range Forecasting general circulation model, at the Max Planck Institute, Hamburg) and ran the model for 80 to 100 years using heat flux patterns (heat transport from the surface into the atmosphere or vice versa) related to the recent positive and negative extremes of the Atlantic Multidecadal Variability (AMV) for three differing regions in the North Atlantic and Arctic.

The authors’ work demonstrated the AMV forced heat fluxes project statistically significant temperature and pressure changes onto the Northern Hemisphere climate, including influencing the NAO. The authors conclude, “the results show that such an internal and regionally confined climate variation can drive relatively large surface climate anomalies on regional, hemispheric, and even global scales. The Arctic plays an important role in this, explaining about 60% of the total Northern Hemisphere surface air temperature response.” They also point out these results are applicable to recent decades. However, in their study the forcing of the Arctic on lower latitudes such as Europe is always in the same direction (warmer Arctic means warmer Europe), contradicting the “Warm Arctic-Cold Continents” conjecture.

The results of Semenov *et al.* and Petoukhov and Semenov are not surprising, as it has been theorized for some time that multidecadal oscillations, or natural variations, can imprint on regional, hemispheric, or even global climate change. However, in both studies, the modeling strategy is meant to test the sensitivity of the models to forced interdecadal variability. In neither study was the model able to capture interdecadal variability as it occurs in nature. Additionally, neither paper explicitly endorsed its results as being supportive of anthropogenic global warming as some have claimed. Although Semenov *et al.* are careful to add statements of assurance that their results do not contradict the

global warming orthodoxy, they offer no evidence in support of it.

Lienert *et al.* (2011) state “climate models are increasingly being used to forecast future climate on time scales of seasons to decades,” and “since the quality of such predictions of the future evolution of the PDO [Pacific Decadal Oscillation] likely depends on the models’ ability to represent observed PDO characteristics, it is important that the PDO in climate models be evaluated.”

Working with observed monthly-mean SST (sea surface temperature) anomalies they obtained from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version-1 (Rayner *et al.*, 2003) data set for 1871–1999, as well as the extended reconstructed SST version-3b data set (Smith *et al.*, 2008), Lienert *et al.* assessed the ability of 13 atmosphere-ocean global climate models from the third phase of the Coupled Model Intercomparison Project (CMIP3), conducted in support of the IPCC *Fourth Assessment Report* (Solomon *et al.*, 2007), to “reproduce the observed relationship between tropical Pacific forcing associated with ENSO and North Pacific SST variability associated with the PDO.”

The three Canadian researchers found “the simulated response to ENSO forcing is generally delayed relative to the observed response,” a tendency they say “is consistent with model biases toward deeper oceanic mixed layers and weaker air-sea feedbacks.” They found “the simulated amplitude of the ENSO-related signal in the North Pacific is overestimated by about 30%” and “model power spectra of the PDO signal and its ENSO-forced component are redder than observed because of errors originating in the tropics and extratropics.”

Lienert *et al.* describe three implications of their findings. First, “because the simulated North Pacific response lags ENSO unrealistically, seasonal forecasts may tend to exhibit insufficient North Pacific responses to developing El Niño and La Niña events in the first few forecast months.” Second, “at longer forecast lead times, North Pacific SST anomalies driven by ENSO may tend to be overestimated in models having an overly strong ENSO, as the models drift away from observation-based initial conditions and this bias sets in.” And third, “the relative preponderance of low-frequency variability in the models suggests that climate forecasts may overestimate decadal to multidecadal variability in the North Pacific.”

Kim *et al.* (2012) state “the Coupled Model Intercomparison Project Phase 5 (CMIP5) has devised

an innovative experimental design to assess the predictability and prediction skill on decadal time scales of state-of-the-art climate models, in support of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report,” citing Taylor *et al.* (2012). To date, however, they note decadal predictions from different CMIP5 models “have not been evaluated and compared using the same evaluation matrix,” a problem they resolve with their study for some of the models. Kim *et al.* assessed the CMIP5 decadal hindcast-forecast simulations of seven state-of-the-art ocean-atmosphere coupled models for situations where “each decadal prediction consists of simulations over a 10-year period each of which are initialized every five years from climate states of 1960/1961 to 2005/2006.”

The three U.S. researchers report “most of the models overestimate trends,” in that they “predict less warming or even cooling in the earlier decades compared to observations and too much warming in recent decades.” They also report “low prediction skill is found over the equatorial and North Pacific Ocean” and “the predictive skill for the Pacific Decadal Oscillation index is relatively low for the entire period.” They conclude “the prediction of decadal climate variability against a background of global warming is one of the most important and challenging tasks in climate science.”

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1.4.3 Intertropical Convergence Zone

It is well-known among scientists in the climate modeling community that GCMs erroneously produce a double Intertropical Convergence Zone (ITCZ) in the Central Pacific much more often than is typically observed. The ITCZ is a “belt” of low pressure that girdles the equatorial tropics and identifies the convergence of Earth’s trade wind belts. Usually, a double ITCZ is observed in the Central Pacific during the Northern Hemisphere spring season only, and not during the rest of the year.

Flaws in the construction of the models, in their numerics and in their physics, are discussed often. But analyses using even erroneous models can sometimes be useful not only in learning where models are deficient but also in identifying where or how the observations need to be improved.

Liu *et al.* (2012) used the Community Climate System Model version 3 (CCSM3), which includes an atmospheric model, a land surface model, and a dynamic ocean model. The model was of intermediate resolution in the horizontal, the equivalent of 2.8 degrees latitude/longitude. There are 26 model layers in the atmosphere. The authors focused on the first one to two years of the model integration in order to locate the problems causing the double ITCZ over the tropics between 170° E and 150°W. The observed data used as input were archived at the Massachusetts Institute of Technology, and the cloud data were

derived from the International Satellite Cloud Climatology Project.

Liu *et al.* learned warm biases in the sea surface temperatures developed within two years of the initial start-up, and these became substantial and similar to those of other studies after five simulation years. The CCSM model also produced a cold bias south of 10°S. The warm bias was present in all seasons. The effect of the warm and cold bias was to establish unrealistic temperature gradients, which in turn affected the winds and the latent heat flux (moisture) into the atmosphere.

The authors additionally found the warm bias was due to excessive solar radiation, at least at first, augmented by excess latent heating later. The root cause was less cloudiness in the model than was observed in the region. These biases induced errors in the ocean structure of the region studied, resulting in a modeled eastward current where a westward current exists in the observations. An experiment was then run by artificially increasing the cloudiness within the region and the problems described above were alleviated.

Liu *et al.* eventually traced the problem of insufficient cloudiness in the study region to low cloud liquid water path in the model (Figure 1.4.3.1), but “whether this is due to insufficient absorption of solar radiation in clouds, or insufficient cloud amount or aerosols, is not clear.”

The goal of Liu *et al.*’s work was to determine how the CCSM model developed a double ITCZ in the Central Pacific. This double Central Pacific ITCZ appears to be a problem for many models. The appearance of a double ITCZ means a model fails to simulate tropical climate well and, given the interactions of this region with the mid-latitudes, these simulation problems would be felt in the model far from the study region.

Reference

Liu, H., Zhang, M., and Lin, W. 2012. An investigation of the initial development of the double-ITCZ warm SST biases in the CCSM. *Journal of Climate* **25**: 140–155.

Climate Change Reconsidered II

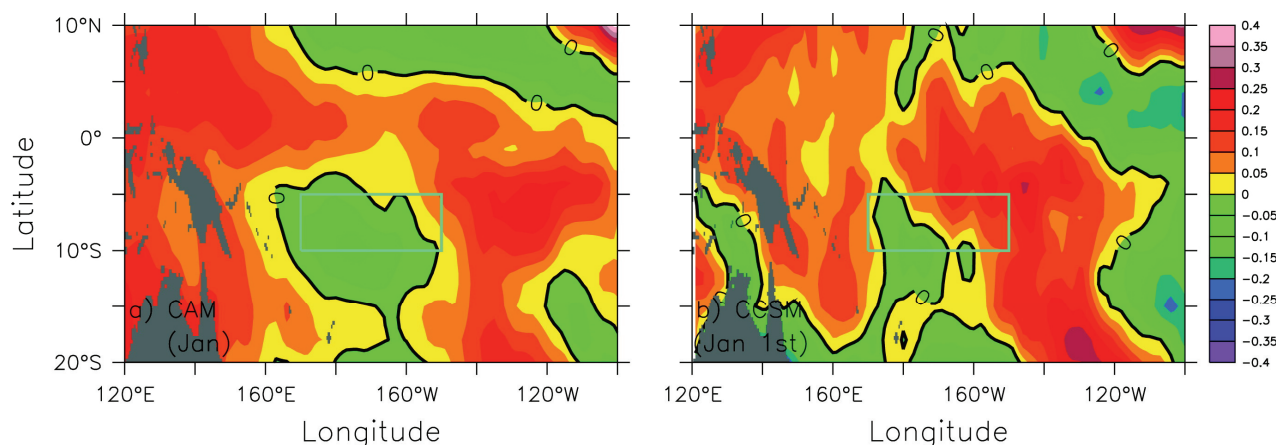


Figure 1.4.3.1. The differences in the total cloud amount between the model and observed cloudiness (%) for the first month of the (a) atmospheric model only, and (b) the full CCSM ensemble mean. The green box bounded by 170°E and 150°W and 5° to 10°S is the domain over which the authors studied the heat budgets. Reprinted with permission from Liu, H., Zhang, M., and Lin, W. 2012. An investigation of the initial development of the double-ITCZ warm SST biases in the CCSM. *Journal of Climate* **25**: 140–155.

1.4.4 South Pacific Convergence Zone

The South Pacific Convergence Zone (SPCZ) is a permanent feature in the general circulation that stretches southeastward from the equatorial region of the west Pacific into the central mid-latitude Pacific near Polynesia. This band of precipitation has drawn the interest of the climatological community because it behaves like the ITCZ in the tropics but is driven by jet-stream dynamics in the mid-latitudes. Like the ITCZ, it is a locus for the occurrence of precipitation in the regions it impacts.

Previous research has demonstrated the observed behavior and location of the SPCZ varies in relation to the phase of El Niño. During an El Niño year, the SPCZ is located closer to the equator and can be oriented in a more zonal fashion, and these changes are more robust during stronger El Niño events. At such times, Indonesia, Australia, and southwest Pacific nations are subjected to reduced rainfall, which of course affects the regional ecology.

In a letter to *Nature*, Cai *et al.* (2012) compared the larger-scale components of the SPCZ rainfall anomalies derived from observations during the period 1979–2008 to rainfall anomalies generated by 17 CMIP3 general circulation model simulations covering the period 1891–2000. These simulations included known natural and anthropogenic forcings. The team of researchers then generated 90-year simulations using the A2 greenhouse emission scenarios, which assume business as usual or accelerating greenhouse gas emissions. Cai *et al.* also applied the same strategy with CMIP5 models under a

scenario that levels out at 850 ppm during 200 years assuming 1 percent increases per year until stabilization. This is similar to the A2 scenario.

The work of Cai *et al.* revealed stronger SPCZ events will occur with greater frequency in the future under the increased greenhouse gas scenarios in both models (doubled in CMIP3 and tripled in CMIP5). This implies increased frequency of drought for the regions of the southwest Pacific. Both models also implied stronger El Niño events occur more frequently in the future scenario, but not as frequently as the increased SPCZ occurrences. Curiously, these results also imply SPCZ behavior decouples from that of El Niño.

The conclusion that stronger SPCZ events will occur in the future was based on a greenhouse gas emission scenario considered quite extreme. Additionally, although there may be a physical reason for future decoupling of the relationship between SPCZ strength and location and the strength of El Niño, it should be noted the modeled SPCZ orientation seems to be more zonal than observed even before the future scenarios are generated (compare Figure 1.4.4.1 and Figure 1.4.4.2).

The authors admit to some uncertainty in the observed SPCZ position: “Although the simulated frequency in the control period is comparable to the observed frequency, the latter is based on observations over some three decades and may carry a large uncertainty.” Like many modeling studies, the outcome of Cai *et al.* is properly understood as nothing more than a scenario based on a specific set

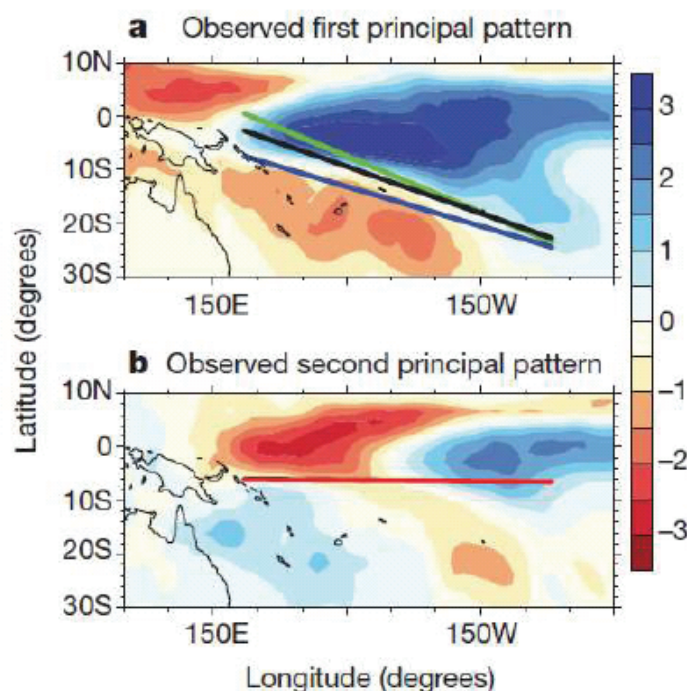


Figure 1.4.4.1. The variability of observed rainfall for the (a) spatial pattern of the largest-scale component of the observed precipitation anomalies that was filtered out, and (b) second-largest component of the observed anomalies extracted from the satellite-era rainfall anomaly data (mm d^{-1}) (Global Precipitation Climatology Project version 225) focusing on the western South Pacific during the austral summer (December to February). The first (second) principal patterns account for 47% (16%) of the total variance. The SPCZ position (max rainfall greater than 6 mm d^{-1}) for El Niño (green line), La Niña (blue line), and neutral (black line) states is superimposed in a, and the position for zonal SPCZ events (red line) in b. Cold (warm) contours indicate increased (decreased) rainfall per one standard deviation (s.d.) change. Reprinted with permission from Cai, W., Languagne, M., Borlace, S., Collins, M., Cowan, T., McPhadden, M.J., Timmermann, A., Power, S., Brown, J., Menkes, C., Ngari, A., Vincent, E.M. and Widlansky, M.J. 2012. More extreme swings of the South Pacific Convergence Zone due to greenhouse warming. *Nature* **488**: 365-369, Figure 1.

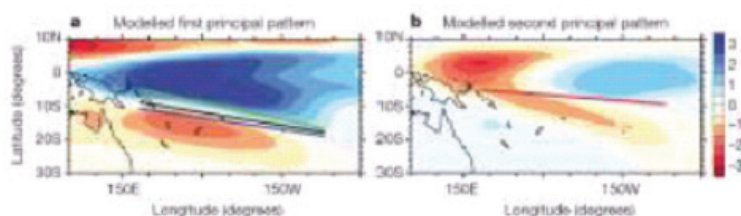


Figure 1.4.4.2. As in Figure 1.4.4.1, except for the CMIP model runs.

of assumptions, with limitations on the ability to capture the phenomenon in question precisely. Their results have only limited scientific value.

Reference

Cai, W., Languagne, M., Borlace, S., Collins, M., Cowan, T., McPhadden, M.J., Timmermann, A., Power, S., Brown, J., Menkes, C., Ngari, A., Vincent, E.M. and Widlansky, M.J. 2012. More extreme swings of the South Pacific Convergence Zone due to greenhouse warming. *Nature* **488**: 365-369.

1.4.5 Hadley Circulation

The Hadley Circulation, or Hadley Cell, is an important general circulation of Earth's climate. It is named for Sir George Hadley, who first attempted to describe Earth's circulation in a general way. Warm equatorial air rises, while cold polar air sinks, and a hemisphere-wide circulation loop is formed. Hadley was partly correct but failed to account for the Coriolis Effect, which was discovered by later researchers.

The Hadley Cell emerges from an analysis of the tropics when atmospheric motions are averaged on the time scale of a month or more. In a classical view of this circulation, there are upward motions and low pressure at the equator (mainly associated with deep convection clouds), poleward moving air aloft, downward motion around 30° latitude, associated with the subtropical highs, and equatorward moving air (the trade winds) in the lower atmosphere. Studies have suggested the latitudinal extent of the Hadley Cell may have widened in the past few decades.

Levine and Schneider (2011) used a crude atmospheric general circulation model to examine the strength and span of the HC over a wide range of climates. They performed this study because some studies show the HC strengthens, while others show it weakens, in response to global warming. As Levine and Schneider report in describing the rationale behind their study, "despite a large body of observations and numerous studies with GCMs, it remains unclear how the width and strength of the

Hadley Circulation are controlled.”

Levine and Schneider used an idealized radiative transfer scheme and moist thermodynamics. The model was based on one used at the Geophysical Fluid Dynamics Laboratory, a model with relatively coarse resolution (about 2.8° latitude/longitude) and 30 levels in the vertical. The planet “surface” was water-covered only. The oceans included simple dynamics for heat transport (which was turned “on” and “off”), and the model was driven with the annual mean insolation, thus there was no diurnal or annual cycle. In this way the authors could isolate two variables, the strength of the HC versus global temperature (controlled by the absorption of longwave radiation only).

The authors established a baseline climate for their aqua-planet and ran the model with and without ocean dynamics. The results were more realistic with the ocean dynamics. Then, the longwave absorption, a function of latitude and pressure (height), was varied by a constant amount between 0.2 and 6.0 times the control value. This produced a global climate with planetary temperatures varying between 260 K and 315 K (roughly -13°C to 42°C ; today it is roughly 15°C). The equator-to-pole temperature differences decreased linearly with increasing temperature.

In their simulations, the strength of the Hadley Cell did not change linearly (Figure 1.4.5.1) but rather was more parabolic in shape, which makes the situation more complicated. The Hadley Circulation in their model was weaker in both very cold and very warm climates. Also, Figure 1.4.5.1 implies ocean dynamics become less important in determining the strength of the Hadley Circulation as climate warms. This is true because the equator-to-pole temperature difference becomes negligible. In colder climates, the weakening is the result of a more geostrophic, or zonal, atmospheric flow. A more zonal flow would imply less wave action in the jet stream, which means less energy exchange. Today’s climate is roughly at the maximum in the ocean dynamics curve.

The behavior of atmospheric systems can be complicated even when there are few variables. This has led to studies whose findings initially seem to be contradictory, for example, in a warmer climate. The behavior of changes in the strength of the Hadley Circulation is nonlinear even in the simple model of Levine and Schneider (2011). Adding complexity to the model would make interpretation of the output more difficult. This demonstrates the importance of understanding the fundamental behavior of phenomena like the Hadley Circulation.

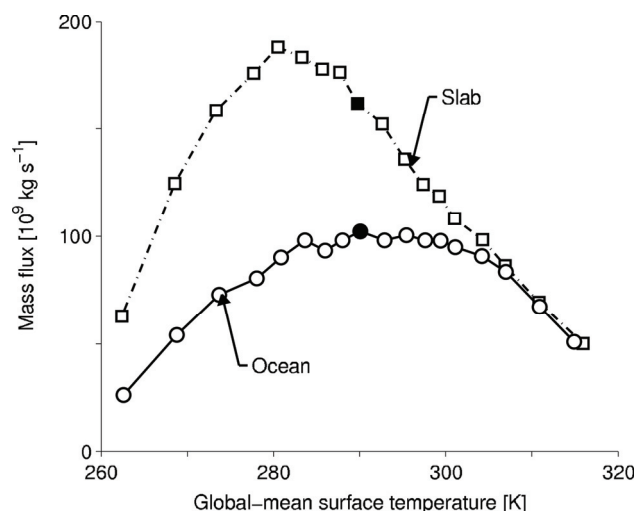


Figure 1.4.5.1. The strength of HC in simulations with (solid, circles) and without (dashed, squares) ocean dynamics. Shown is the absolute value of the mass flux at the latitude of its maximum and at the level $\sigma_c = 0.7$, averaged for both hemispheres. The filled symbols are the reference simulations. Reprinted with permission from Levine, X.J. and Schneider, T. 2011. Response of the Hadley Circulation to Climate Change in an Aquaplanet GCM Coupled to a Simple Representation of Ocean Heat Transport. *Journal of the Atmospheric Sciences* **68**: 769–783, Figure 4.

Reference

Levine, X.J. and Schneider, T. 2011. Response of the Hadley Circulation to Climate Change in an Aquaplanet GCM Coupled to a Simple Representation of Ocean Heat Transport. *Journal of the Atmospheric Sciences* **68**: 769–783.

1.4.6 The Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is a tropical phenomenon discovered in the early 1970s; it is a 30- to 70-day oscillation in the west-to-east component of the tropical winds between 20°N and 20°S . The MJO has been detected in tropical convection and precipitation, both of which are enhanced in the “trough” phase. Although the dynamics that drive the MJO are not fully understood, it is known to interact with larger-scale phenomena such as tropical cyclones, monsoons, and El Niño and the Southern Oscillation (ENSO), as well as with the general circulation itself. The MJO has been linked to mid-latitude circulations, especially during the warm season and over North America.

General circulation models have had difficulty in

representing the MJO and its impact on larger-scale phenomena could not be captured, due primarily to the inadequate representation of the associated convection. This is but one factor that causes GCMs fail, to a certain degree, in representing the large scale correctly.

Subramanian *et al.* (2011) used the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4) model to examine its ability to capture the MJO, which included an upgrade to the convective parameterization scheme. This upgrade “improves the correlation between intraseasonal convective heating and intraseasonal temperature, which is critical for the buildup of available potential energy.”

The authors used a 500-year simulation of the CCSM4 using pre-1850 conditions as a control run. They then extracted two ten-year periods from these data, each representing the strongest and weakest ENSO variability in the 500-year period. They

compared this data set to observed Outgoing Longwave Radiation (OLR), a commonly used proxy for convection, as well as tropical precipitation and zonal winds at 850 and 200 hPa taken from the NCAR/NCEP reanalyses. Lastly, the authors examined the relationship between the MJO and such general circulation features as ENSO and the monsoons in both the model and observations.

Subramanian *et al.* found the CCSM4 produced a feature that propagated eastward in the “intraseasonal zonal winds and OLR in the tropical Indian and Pacific Oceans that are generally consistent with MJO characteristics.” Thus the model performed well overall in capturing the MJO (Figure 1.4.6.1), but there were still some differences. Whereas the observations produced a strong (weaker) wave number one (two and three) in the data, the modeled MJO showed more coherency among the wave numbers one-three. This suggests stronger Kelvin wave activity at the higher wave numbers in the

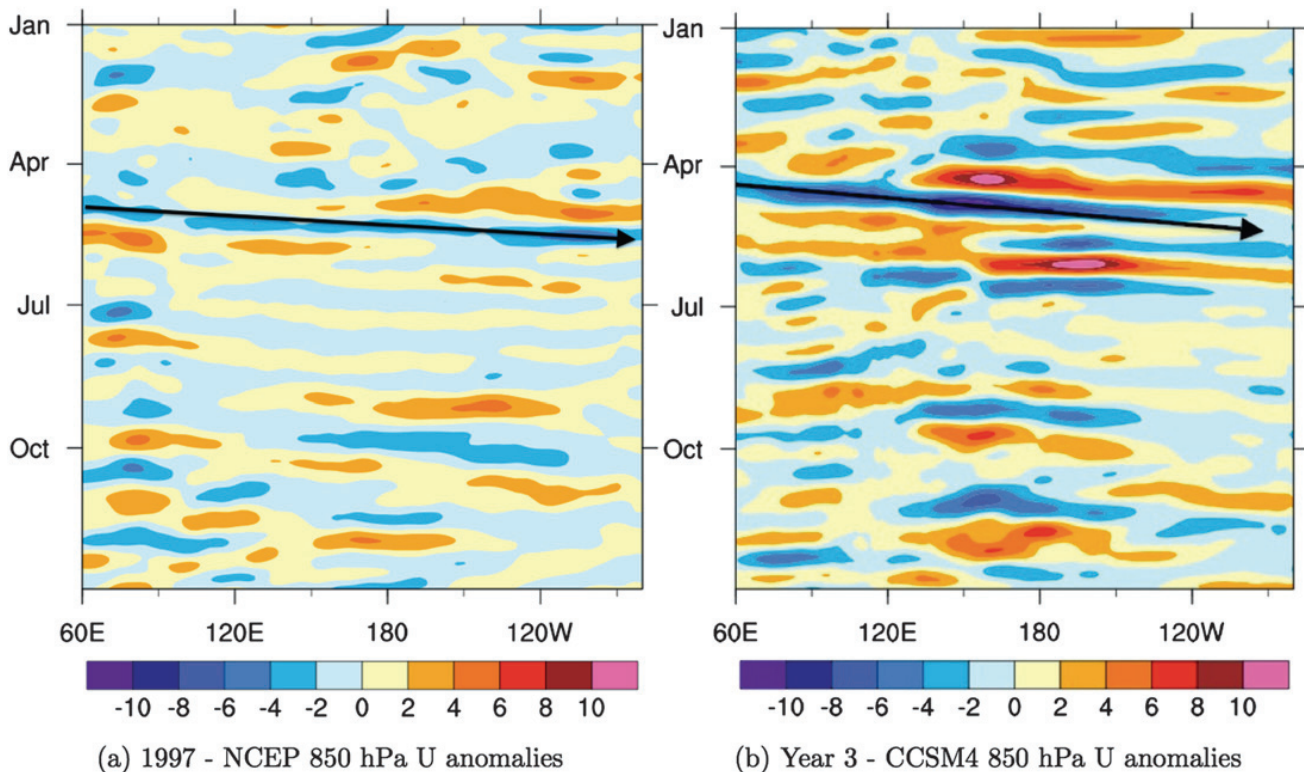


Figure 1.4.6.1. A Hovmöller plot of the zonal winds at 850 hPa filtered to retain the 20-100 day signal for the (a) NCAR/NCEP reanalyses from 1997 and (b) year 3 of the CCSM4 run. The arrow is added to demonstrate the eastward propagation of weaker 850 hPa winds which represents the MJO. Reprinted with permission from Subramanian, A.C., Jochum, M., Miller, A.J., Murtugudde, R., Neale, R.B., and Waliser, D.E. 2011. The Madden-Julian Oscillation in CCSM4. *Journal of Climate* **24**: 6261–6282.

model.

When examining the relationship of the MJO to other phenomenon, the authors found MJO activity was enhanced (weaker) during El Niño (La Niña) years. Also, the MJO occurred more often in the Indian Ocean monsoon region during negative shear regimes (shear defined by the zonal wind at 850 hPa minus the meridional [north-south] wind at 200 hPa). The MJO occurred more often when the Hadley Circulation in the tropics was weaker as well. These phenomena are interrelated, and thus the authors state, the “MJO could thereby be simultaneously affected in multiple ways when these type of large-scale climate mode interactions occur and possibly feed back onto the entire coupled system.”

The outcome of this work demonstrates how difficult it is to represent the current state of the climate, as well as the interannual variability in the climate system. Models continue to improve through the increase in resolution and improvement in sub-grid-scale physical processes. Even though this model showed a distinct improvement in representing the MJO, there were still some differences between the model and the observed MJO. The MJO represents only one critical link between the small-scale atmospheric motions and the general circulation.

Reference

Subramanian, A.C., Jochum, M., Miller, A.J., Murtugudde, R., Neale, R.B., and Waliser, D.E. 2011. The Madden-Julian Oscillation in CCSM4. *Journal of Climate* **24**: 6261–6282.

1.4.7 Atmospheric Blocking

A phenomenon not often discussed in climate change studies is atmospheric blocking, which develops when there is a stationary ridge of high pressure in the mid-latitude jet stream. This phenomenon is typically associated with unusually warm and dry weather in areas where these high-pressure ridges form, and cooler or wetter conditions upstream and downstream of where they occur. The Western European heat wave of 2003, the extreme heat in Russia in 2010 and the downstream flooding in Pakistan, and the cold temperatures over most of North America and Europe during December 2010 are recent examples of blocking and its impact on regional weather.

The first investigation into blocking characteristics in an increased CO₂ and warmer environment was performed by Lupo *et al.* (1997)

using the Community Climate Model version 1 (CCM1). The results of their blocking climatology using CCM1 were comparable to those of Bates and Meehl (1986), who used CCM0B. Both of these efforts found significant differences from observations: in the Atlantic there were fewer events, and in the Northern Hemisphere there were more summer season events. Model blocking also was weaker and less persistent than observations.

When present-day CO₂ concentrations were doubled, the researchers generally found blocking anticyclones were more persistent but weaker than their counterparts in the control experiment. All other characteristics of the overall sample—such as frequency of occurrence, size, preferred genesis locations, and annual variations in size and intensity—were generally similar to the control experiment. The regional and seasonal analysis identified significant differences between the two climatologies. Perhaps the most striking difference was the threefold or more increase in continental region block occurrences and total block days, due to the appearance of the observed western Asian Continental maximum in the double CO₂ run. There also was an increase in blocking frequency over the North American continent compared to the control and observations.

A newer investigation into the blocking phenomenon by Kreienkamp *et al.* (2010) used National Centers for Atmospheric Research re-analyses to examine the occurrence of blocking events over Europe since the 1950s, using a well-known blocking index (Tibaldi and Molteni, 1990). Kreienkamp *et al.* employed the atmospheric general circulation model (ECHAM) used by the IPCC in an effort to determine how well the model simulated such blocking. They also examined two climate warming scenarios (A1B and B1) for the twenty-first century in order to infer whether blocking will become more or less common in based on model projections.

With respect to the re-analysis data, Kreienkamp *et al.* found little evidence of a statistically significant trend over the period 1951–2007 apart from a weak decrease in the European region; this decrease suggests extreme weather events caused by blocking events probably have also declined. With respect to model simulations, they found the models showed little change in the frequency, seasonality, or interannual variability of blocking for the Atlantic/European region as a whole but a significant decrease in Central European region frequency.

Global Climate Models and Their Limitations

Another study of blocking by Scaife *et al.* (2010) set out to determine whether model error in the large- or small-scale processes is responsible for the underestimate of blocking. They first produced a blocking climatology using the Hadley Centre Global Environmental Model (HadGEM), an atmospheric general circulation model. They used a version of the zonal index to diagnose blocking (Berrisford *et al.*, 2007) and observed data archived at the European Centre for Medium Range Forecasting (ERA-40 re-analyses) for comparison (Figure 1.4.7.1). Then the authors extended the study to 18 other simulations produced using various GCMs for the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report*.

gradients) show large errors in current climate models, but these are directly attributable to a large degree to errors in the main state.” Scaife *et al.* also show improvements in the large-scale model performance can greatly improve the capability of the model to reproduce blocking characteristics.

The latest study by Mokhov *et al.* (2013) for the projection of blocking in the twenty-first century using the Institut Pierre Simon Laplace Climate Model versions 4 (IPSL-CM4) GCM and the SRES-A1B and SRES-A2 scenarios showed a slight increase in the number and persistence of blocking events over the Atlantic-Eurasian region and no change in the interannual or interdecadal variability. These results are similar to the other studies examined here.

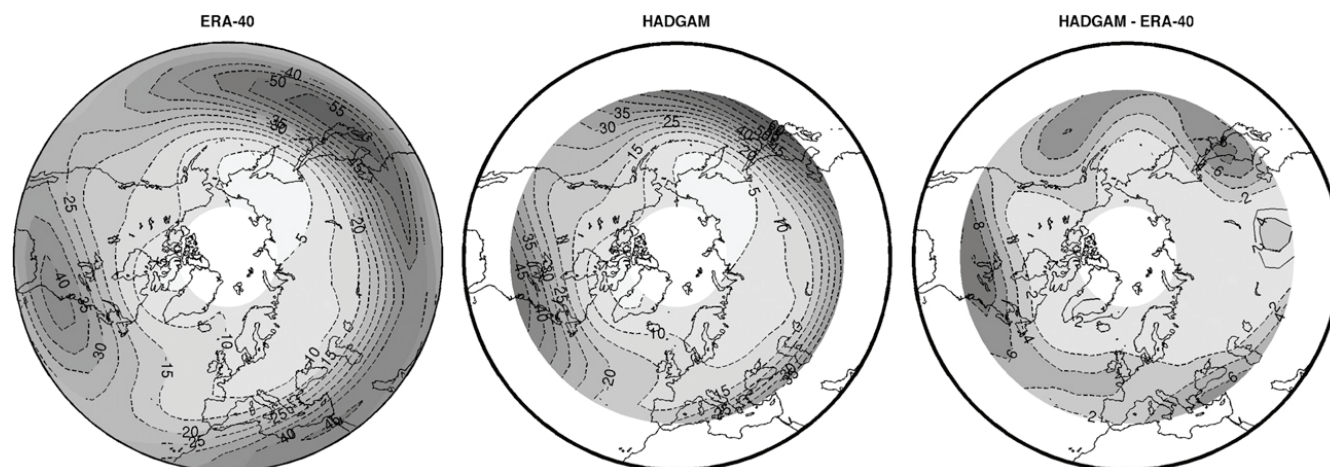


Figure 1.4.7.1. The climatological frequency of the winter season blocking using the Berrisford *et al.* (2007) index (not blocking frequency). Shown are the (left) ERA-40 reanalyses, (middle) HadGEM Model, and (right) the model error. The hemispheric nature of the model error shows that it is present at all longitudes. Units are K^{-1} . Reprinted with permission from Scaife, A.A., Wollings, T., Knight, J., Martin G., and Hinton, T. 2010. Atmospheric blocking and mean biases in climate models. *Journal of Climate* **23**: 6143–6152.

Since the zonal index is generally used to represent blocking, the authors separated the zonal mass gradient produced by the HadGEM model and in the observed data into a climate mean (large-scale) component versus that of the time-varying portion (small-scale). When they replaced the large-scale model data with the observed (keeping the small-scale model part), they showed the blocking frequency was reproduced more faithfully. The same result was found in the IPCC simulations and by Lupo *et al.* (1997).

Scaife *et al.* state, “commonly applied statistics based on absolute measures (such as the reversal of the geopotential height or potential vorticity

Although caution should be emphasized in interpreting the model projections, the findings of these studies are good news, for they suggest the number of heat waves and/or cold waves that can be attributed to atmospheric blocking will not increase for the Atlantic/European region in the twenty-first century. In fact, the model output suggests fewer of these occurrences and/or a shorter duration of such events (e.g., Kreienkamp *et al.*, 2010).

Studies by Liu *et al.* (2012) and Jaiser *et al.* (2012) find an increase in observed blocking since 1995 consistent with that found by Mokhov *et al.* (2013), but rather than linking this to internal variability, including changes in the phases of

multidecadal oscillations, they attribute the change to anthropogenic climate warming. A paper by Hakkinen *et al.* (2011) takes a more measured approach, stating, “the warm-ocean/cold-land anomaly pattern has been linked to a dynamical environment favorable for blocking” and “the possibility of coupled interaction of atmosphere with [Atlantic Multidecadal Variability] seems likely, given the long-period variability of blocking reported here and in the even longer paleoclimate time series.” The latter position is more consistent with the studies reviewed here.

Two studies provide additional evidence for the lack of trends in Northern Hemisphere blocking patterns. Screen and Simmonds (2013) studied “observed changes (1979–2011) in atmospheric planetary-wave amplitude over northern mid-latitudes, which have been proposed as a possible mechanism linking Arctic Amplification (AA) and mid-latitude weather extremes.” However, they found few if any large or statistically significant changes, instead noting “Statistically significant changes in either metric are limited to few seasons, wavelengths and longitudinal sectors” and “Even ignoring the lack of significance, there is no clear tendency towards larger or smaller [wave amplitude] (60% negative trends and 40% positive trends). Nor is there a general tendency towards longer or shorter wavelengths (i.e., longer wavelengths are not increasing in zonal amplitude at the expense of shorter wavelengths), or vice versa.”

Most recently, Barnes (2013) investigated “trends in the meridional extent of atmospheric waves over North America and the North Atlantic ... in three reanalyses.” Barnes’s work “demonstrated that previously reported positive trends are an artifact of the methodology” and further “the mechanism put forth by previous studies (e.g. Francis and Vavrus [2012]; Liu *et al.* [2012]), that amplified polar warming has led to the increased occurrence of slow-moving weather patterns and blocking episodes, is unsupported by the observations.”

One of the criticisms of model projections used to produce climate change scenarios for the twenty-first century is that the models still have difficulty reproducing various aspects of the observed climate, including even the large-scale features (Scaife *et al.*, 2010). Blocking is one of these phenomena, and it is often used as a surrogate for the occurrence of extreme conditions (heat waves, cold waves). If the models cannot adequately represent blocking in the current climate, results regarding the occurrence of

extreme events in future climate change scenarios must be examined with caution.

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1.4.8 Tropical Cyclones

Tropical cyclones (TCs) form and are maintained by the cooperative forcing between the atmosphere and oceans. Warm tropical waters (sea surface temperatures or SSTs) are the energy source needed to generate and maintain them, but favorable atmospheric conditions (e.g., low wind shear) are just as critical. These atmospheric conditions can be correlated to warm tropical SSTs. But warmer SSTs by themselves do not always portend more TCs. Some general circulation model studies have projected there will be as much as a 200 percent increase in TC occurrence in a warmer world, while other GCM studies suggest such a world will bring fewer TCs.

Villarini *et al.* (2011) attempted to explain why there is a large spread in the projection of TC occurrences that may occur in the future. They used a statistical model trained using a 131-year record of North Atlantic TC occurrences, a Poisson regression type model that generated land-falling or Atlantic TC frequencies as a function of Atlantic region and/or tropical mean SSTs. The SSTs included variability related to the North Atlantic Oscillation (interdecadal) and the Southern Oscillation Index (interannual). The authors compared the statistical model results with those produced by dynamic GCMs and statistical-dynamic models for the Intergovernmental Panel on Climate Change (IPCC). In order for the comparisons to be more faithful, the authors used the SST time series in the statistical model that each particular IPCC model scenario used.

When both the Atlantic region and tropical mean SSTs were used, there was good agreement between the results of the statistical model and that of the dynamic models (Figure 1.4.8.1). Tropical SSTs elsewhere can affect Atlantic TC occurrence via variations in the jet stream. The authors note, “the agreement between the statistical and dynamical models is rather remarkable, considering the simplicity of the statistical model.” They also state “it appears that the differences among the published results can be largely reduced to differences in the climate model projections of tropical Atlantic SST changes relative to the global tropics used by the studies.”

When Villarini *et al.* used Atlantic SST alone, there was little agreement between the statistical and dynamic models, with the statistical models showing large biases in TC frequency. The dynamic models did not show this bias, supporting the notion that SSTs alone cannot explain variations in TC occurrence. There were also mixed signals produced by the IPCC models with regard to landfalling TCs, half showing a statistically significant increase and the other half showing a significant decrease. The authors suggest that in order to reduce the uncertainty in future TC occurrence, the uncertainty in tropical Atlantic and tropical mean SSTs and their difference should be reduced.

With respect to claims that increases in TC frequency and strength will occur as a result of anthropogenic global warming, and coastal areas will be more vulnerable to destruction, the authors state, “the results do not support the notion of large (~200%) increases in tropical storm frequency in the North Atlantic Basin over the twenty-first century in response to increasing greenhouse gasses (GHGs).” Instead they found it is more likely TC frequency may change by +/- 40% by the late twenty-first century and this “is consistent with both the observed record and with the range of projections of SST patterns.”

Models also have had difficulty replicating the dynamic structure of tropical cyclones. This is partially due to the vertical exchanges being dominated by deep convection, which is on a scale below the resolution of the grid. Another contributing factor is that the models’ resolution is insufficient to define the relatively small scale circulation, especially the eye wall where the circulation is most intense. In addition, the paucity of observations means the factors triggering tropical cyclone development are poorly known. Early atmospheric general circulation models (AGCMs) had horizontal resolutions the equivalent of approximately 450 km. In such a model, resolving individual storm events was impossible, and these could only be inferred from the aggregate statistical properties of quantities such as momentum or temperature flux.

Manganello *et al.* (2012) employed the European Centre for Medium-Range Weather Forecasts (ECMWF) IFS model to examine the climatology of TCs by identifying individual events. This model is the recent version of the ECMWF GCM and includes the latest physical packages for cloud formation (i.e., prognostic equations for cloud water), land surface processes and hydrology, and improved convective adjustment schemes. The latter provided for a better

Percentage Change in Tropical Storm Frequency

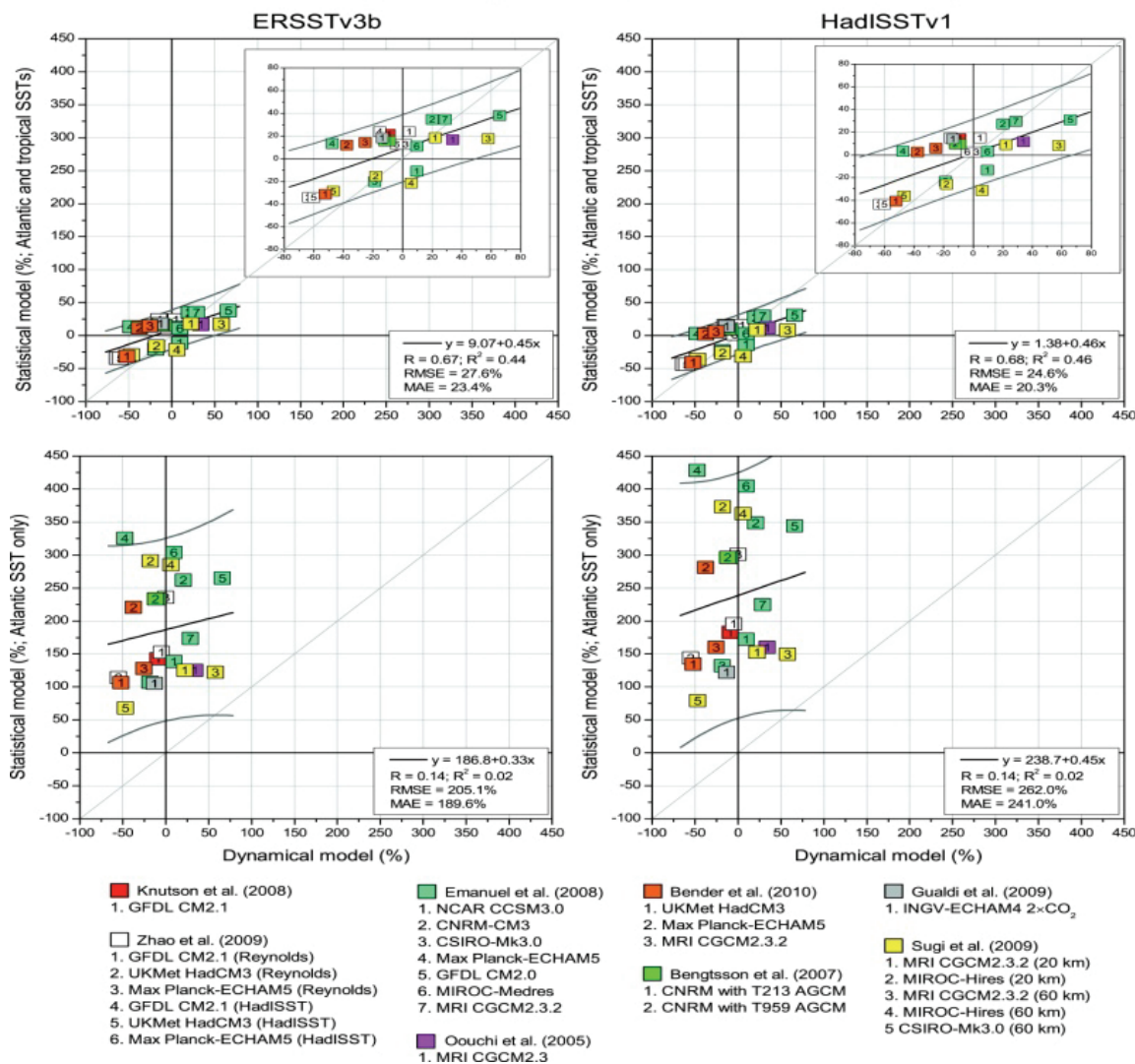


Figure 1.4.8.1. A comparison of the fractional TC count changes between the statistical model and IPCC dynamic models. The top (bottom) figures show the use of Atlantic region and tropical (Atlantic region only) SSTs. The left (right) side panels were formulated using the NOAA ERSSTv3b (HadISSTv1) dataset. The gray lines define the 90% prediction interval for the linear regression model. Reprinted with permission from 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.

representation of tropical weather and year-to-year variations in tropical climate.

The model was run for “Project Athena” (Jung *et al.*, 2012) with resolutions at 125 km, 39 km, 16 km (the current resolution of a weather forecast model), and 10 km; for all there were 91 levels in the vertical. The model also was run for each year from 1960 to 2008 for the larger resolutions, and for 1989–2008 for the 10 km run. To keep the data storage manageable, the authors used data for May through November in

the Northern Hemisphere (NH) for 1990–2008. The authors also controlled the data to make sure storms identified were indeed TCs, such as requiring a warm core, meaning the center is warmer than the surrounding environment.

Manganello *et al.* found over the entire NH, the 39 km run produced the most realistic count for TCs; the higher resolution model produced too many TCs. Within each basin (e.g., Atlantic) or sub-basin (Northwest Pacific), however, the higher resolutions

occasionally produced the best results. One problem for models is tropical cyclogenesis tends to be too weak, and it was a problem here in spite of better resolution. In a related problem, the model produced TCs that were weaker than observed in terms of wind speed but comparable in terms of central pressure (Figure 1.4.8.2). Finally, the higher model resolution runs did better in capturing ENSO variability of TCs. ENSO is well-known to have a large influence on the interannual variation of TC occurrence and intensity.

Manganello *et al.* note, “as computing power continues to grow, it is becoming increasingly possible to model the global climate at horizontal resolutions presently used in short-term weather

prediction.” Although hindcasts with improved resolution and physics still have difficulty representing observations to a high degree, the models are able to reasonably reproduce the number of events, and even produced structures that look like observed TCs (Figure 1.4.8.3), thus, passing the test. These kinds of advances represent progress and should make future computer scenarios for climate more reasonable and useful.

The studies of Dare and McBride (2011) and Park *et al.* (2011) have demonstrated tropical cyclones (TCs) can significantly cool the surface waters in their wakes for periods of several days to weeks. Manucharyan *et al.* (2011) write, “TC-induced ocean mixing can have global climate impacts as well, including changes in poleward heat transport, ocean circulation, and thermal structure.” They note, however, that “in several previous modeling studies devoted to this problem, the TC mixing was treated as a permanent (constant in time) source of additional vertical diffusion in the upper ocean.” They thus explore the “highly intermittent character of the mixing” and what it portends for global climate, using a global ocean-atmosphere coupled model and a simple heat transfer model of the upper ocean.

The three Yale University researchers mimicked the effects of TCs using several representative cases of time-dependent mixing that yield 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.

Manucharyan *et al.* observed “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 say “additional mixing leads to an enhanced oceanic heat transport from the regions of increased mixing toward high latitudes and the equatorial region.”

“Ultimately,” the researchers state, “simulations with TC-resolving climate models will be necessary to fully understand the role of tropical cyclones in climate,” for “the current generation of GCMs are only slowly approaching this limit and are 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).”

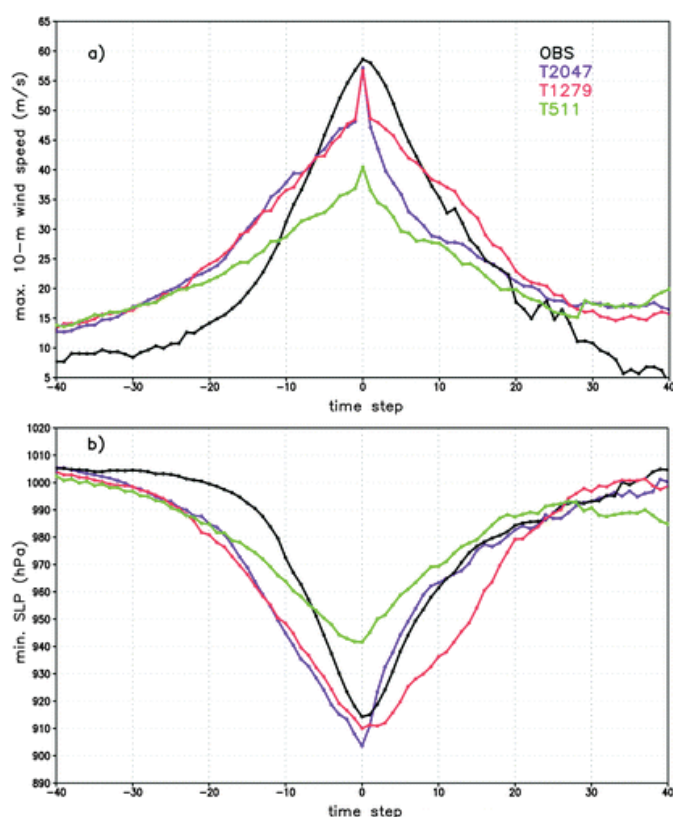


Figure 1.4.8.2. Life cycle composite of the (a) maximum 10-m wind speed and (b) minimum SLP for the 25 most intense typhoons, in terms of the maximum 10-m wind speed, over the northwest Pacific for observed data (black), the 10-km (purple), the 16-km (red), and 39-km (green) runs during MJJASON of 1990–2008. The time step is in 6-h increments. Reprinted with permission from Manganello, J.V., Hodges, K.I., Kinter III, J.L., Cash, B.A., Marx, L., Jung, T., Achuthavarier, D., Adams, J.M., Altschuller, E.L., Huang, B., Jin, E.K., Stan, C., Towers, P., and Wedi, N. 2012. Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather-resolving climate modeling. *Journal of Climate* **25**: 3867–3892, Figure 9.

Climate Change Reconsidered II

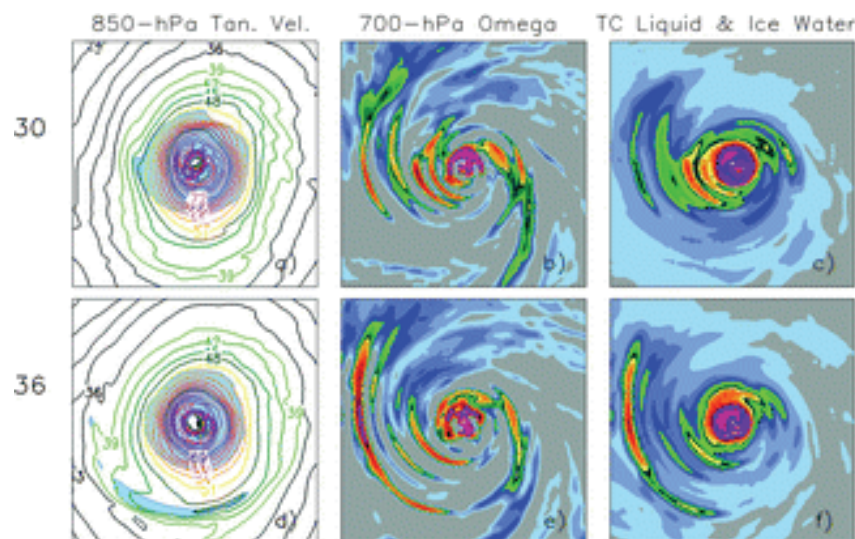


Figure 1.4.8.3. (Left panel) 850-hPa tangential velocity (m s^{-1}), (middle) 700-hPa omega (Pa s^{-1}), and (right) TCLIW (kg m^{-2}) for 30 and 36 hours after onset as shown on the left for an intense TC (10-km resolution). Radius is 3.5° from the storm center. Blue shading on the left roughly delineates the regions where the local wind maxima occur. Adapted from Manganello, J.V., Hodges, K.I., Kinter III, J.L., Cash, B.A., Marx, L., Jung, T., Achuthavarier, D., Adams, J.M., Altshuller, E.L., Huang, B., Jin, E.K., Stan, C., Towers, P., and Wedi, N. 2012. Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather-resolving climate modeling. *Journal of Climate* **25**: 3867–3892, Figure 12.

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1.4.9 Storm Tracks and Jet Streams

The climate of Earth's atmosphere is largely driven by forcing from the underlying surface, of which 71 percent is covered by the oceans. Thus the oceans and mountains are important in simulating storm tracks, and any simulations of present or future climate must

Global Climate Models and Their Limitations

be able to represent the land surface topography and the world oceans in a realistic way if the models are to be useful.

Storm tracks (Figure 1.4.9.1) are the climatological “signature” representing the frequency and strength of the regular passage of cyclonic

involved using extreme and unrealistic parameterizations in order to isolate the impact of certain factors. A scenario was developed in which all land topography was leveled to 1 meter in height and the ocean was a 30-meter “slab” that does not move; a second scenario added mountains; and a third

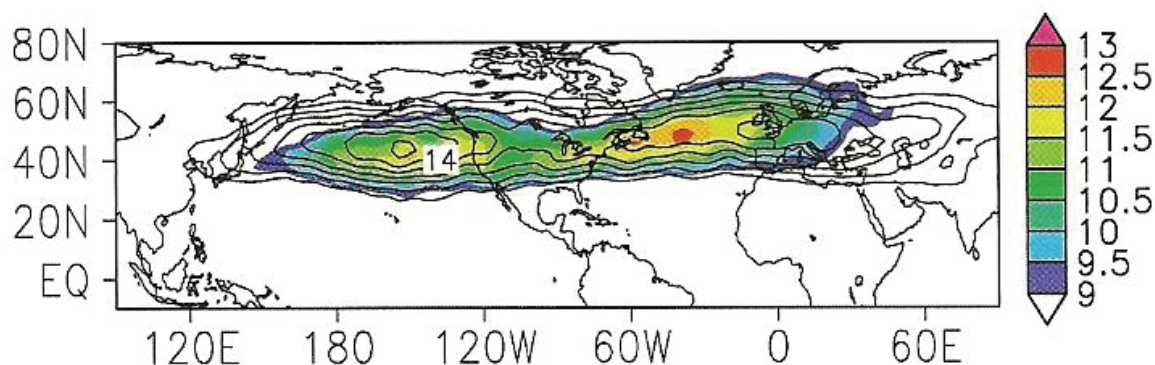


Figure 1.4.9.1. The mean winter Northern Hemisphere storm tracks from the European Center’s observational reanalyses (colors), and the atmospheric general circulation model used in the Wilson *et al.* (2010) study (contours). The storm tracks were derived from the cyclone scale filtered upper air (250 hPa) kinetic energy. Reprinted with permission from Wilson, C., Sinha, B., and Williams, R.G. 2010. The shaping of storm tracks by mountains and ocean dynamics. *Weather* **65**: 320–323.

disturbances. These disturbances are generally responsible for bringing weather that can be a minor nuisance on a typical day, such as rain or snow showers, or as severe weather that can cause loss of life and property. These low pressure systems are also a significant mechanism for the poleward transport of heat, momentum, and water vapor out of the tropics. These actions are necessary for maintaining the structure of Earth’s current general circulation and climate.

Natural variations, as well as global or regional climate change, can induce changes in the storm tracks. As noted by Wilson *et al.* (2010), “as the climate changes, the ocean dynamics will change, but the land and mountains remain unchanged over millennia. Therefore in order to understand how the shape of the storm tracks will evolve, it is crucial to understand the relative impact of ocean dynamics and orography, as well as their interactions.”

Four model worlds were constructed by Wilson *et al.* using a coupled ocean-atmosphere general circulation model. A model control run was performed with realistic topography and a fully dynamic ocean. Then, a typical modeling strategy was used to produce three other runs. This strategy

scenario was created without mountains but containing a fully dynamic ocean.

From the results of the model runs, Wilson *et al.* showed storm tracks are inherent in our atmosphere, as these features were found in the model run even without mountains and topography. In the model runs that included a dynamic ocean, the effect was to push the storm tracks poleward. The impact of the mountains was to reduce storm activity on their leeward side. The two combined features resulted in distinct Atlantic and Pacific storm tracks rather than just one long track in the Northern Hemisphere.

Changes in climate may also alter the storm tracks through changes in the frequency and intensity of the cyclones that comprise them. This would have an impact on the frequency and intensity of related phenomena such as blocking anticyclones. Blocking anticyclones are implicated in contributing to the European and Russian heat waves of 2003 and 2010, respectively. Such events also are implicated in severe winter cold across all continents. Thus, in order to discuss possible future scenarios for the climate or even the occurrence and severity of extreme events, any models used to generate these features must include interactive ocean dynamics.

And as Wilson *et al.* pointed out, “increased resolution is needed in coupled climate models to adequately address the role of ocean dynamics.”

In examining the strength of storms, anthropogenic global warming (AGW) supporters have argued for decades that an increase in CO₂ will bring warmer temperatures and stronger and more destructive storm, including more hurricanes, tornadoes, and mid-latitude cyclones. Recently, they have argued the warmer temperatures will strengthen the water cycle, making these storms even stronger. Models have not been helpful in settling this argument, as some models imply storminess will decrease while others imply the opposite. In addition, empirical observations, which will be discussed in detail in Chapter 7 of this volume, do not support such projections.

The strength of the general circulation is controlled by two main factors. One is the equator-to-pole temperature difference (gradient) and the other is atmospheric stability. These ultimately drive the general circulation and give rise to the jet streams. In the mid-latitudes, where the gradient is strong, storms arise and are driven by these gradients. The ultimate role of storms is to decrease the equator-to-pole gradient. The impact of the horizontal temperature gradient is well-known through knowledge of baroclinic instability. A stronger gradient will generally lead to more storminess.

Hernandez-Deckers and von Storch (2012) (hereafter HDvS12) show the second factor, atmospheric stability, is often overlooked in the climate change debate. Stability is simply the atmosphere’s resistance to overturning where warm air rises and cold air sinks. For example, to make the atmosphere less (more) stable, one could warm (cool) the surface relative to the upper air.

HDvS12 used the European Centre for Medium Range Forecasting general circulation model (ECHAM5) coupled with an ocean model from the Max Planck Institute. They calculated the generation, flow, and dissipation of energy in the atmosphere in order to compare the impacts of temperature gradient and atmospheric stability in changing the strength of the general circulation.

The authors tested the proposition that AGW will warm the poles faster than the tropics near Earth’s surface (SFC, first trial run). This argues for a weakening of the general circulation as horizontal temperature gradients decrease. However, warming the SFC polar region decreased the stability of the model atmosphere. Others have argued AGW will

warm the upper troposphere relative to the surface, especially in the tropics (UP, second trial run). This increases tropical atmospheric stability but increases the upper air temperature gradients. HDvS12 then added the two effects together in a third trial (UP+SFC).

HDvS12 found the general circulation “weakens by almost 10% in the UP experiment whereas it strengthens by almost 4% in the SFC experiment. In the FULL experiment, it weakens by about 5%.” The FULL and the UP+SFC experiments were similar in outcome. They also note “the expected effects due to mean static [atmospheric] stability and meridional temperature gradient change are opposite of each other.” The results demonstrate the stability impact seems to be dominant (Figure 1.4.9.2).

Some scientists have argued storminess should decrease under AGW scenarios due to the weakening

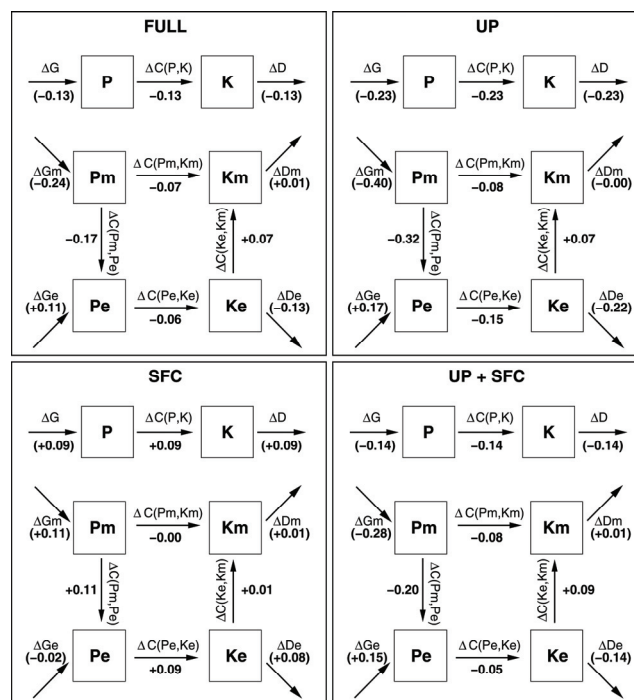


Figure 1.4.9.2. Diagrams of atmospheric energy production, reservoirs, conversions, and dissipation. The numbers given are differences from the control run of the model (today’s climate). The FULL, UP, SFC, and UP+SFC, represent an experiment with double CO₂, warmer upper troposphere only, warmer polar surface temperatures only, and the combined effects, respectively. Units are W m⁻². Arrows indicate the direction of energy flow. Each square contains a simple two box and a more complex four box energy model. Reprinted with permission from Hernandez-Deckers, D. and von Storch, J.S. 2012. Impact of the warming pattern on global energetics. *Journal of Climate* 25: 5223–5240.

Global Climate Models and Their Limitations

of the equator-to-pole temperature differences. That is generally correct but overlooks the impact of atmospheric stability. Models have not sorted out the storminess issue because different models employ different physics for processes that affect the temperature gradient. Models also handle the heating effect of CO₂ differently.

These differences have resulted in surface temperature gradients and upper tropospheric warming of various strengths. But as noted in Section 1.4.6.2, there is no strong observational evidence that the upper troposphere is warming as AGW scenarios suggest. HDvS12 demonstrate the utility of models in breaking down complicated climate problems. More importantly, however, model construction clearly can make a significant difference as to how the outcome is interpreted.

Lang and Waugh (2011) note “understanding the characteristics and trends in summer cyclones is important not only for understanding mid-latitude weather systems and extreme events, but it is also important for understanding the Arctic hydrological cycle and radiation budget (e.g., Orsolini and Sortberg, 2009).” In addition, they note “the surface concentrations of ozone and aerosols, and as a result surface air quality, depend on a range of meteorological factors [that] are closely connected with cyclones (e.g., Jacobs and Winner, 2009).”

Lang and Waugh examined “the robustness of trends in Northern Hemisphere (NH) summer cyclones in the World Climate Research Programme’s Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set that was used in the Fourth Assessment (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007).” The two Johns Hopkins University researchers report they could find “little consistency” among the 16 models they studied. They write, “there is no consistency among the models as to whether the frequency of hemispheric-averaged summer cyclones will increase or decrease.” For some sub-regions, the sign of the trend was consistent among most of the models, but even then, as they report, “there is still a large spread in the magnitude of the trend from individual models, and, hence, a large uncertainty in the trends from a single model.” They conclude, “the general lack of consistency among models indicates that care is required when interpreting projected changes in summer weather systems.”

In another study, Zhang *et al.* (2012) examined the behavior of a jet stream in a channel model of similar length to Earth’s diameter and about 10,000

km in the “north-south” (meridional) direction, with 17 vertical levels centered on a jet maximum. The simplified model used equations representing the basic conservation laws (mass, momentum, and energy) and allowed the “rotation speed” to vary linearly (in reality, it gets stronger from equator to pole). This model also allowed the variation of atmospheric stability in the meridional direction as well as a meridional temperature difference of 43° C, comparable to terrestrial equator-to-pole temperature differences. The model contained surface friction, varied in order to examine the behavior of the jet.

When the surface friction was increased, the researchers found discernible differences in the zonally and time-averaged wind (Figure 1.4.9.3) and temperature gradient (Figure 1.4.9.4) profiles. The differences were more discernible in the temperature fields, and as the friction was increased, the prominent wave number in the model increased from four to six. Values smaller (greater) than wave numbers four (six) are associated with the larger (smaller) scale that is considered the planetary (synoptic) scale. Annular mode behavior could be found only in the larger-scale “climate” for the model at weak frictional values.

Zhang *et al.* thus demonstrated the importance of larger waves in maintaining large-scale jet stream baroclinicity (density differences) and a baroclinic mechanism for the cooperation between synoptic and large-scale eddies in maintaining the persistence of annular mode behavior. The authors note, “as an internal mode of variability, understanding the mechanism that sustains the zonal wind anomalies is useful not only to predict the intra-seasonal variability in the extra-tropics but also for climate change projections.”

These internal variations in the jet stream can represent the maintenance of atmospheric blocking, and both are important to account for in seasonal range forecasting. Also, as the climate changes there may be a change in jet stream behavior, but the internal variations will remain. Conversely, if more complicated models cannot replicate annular mode behavior noted in the observations and the simpler model here in future climate change scenarios, the model projections will be of limited value.

Also exploring the subject were Chang *et al.* (2013), who write that “midlatitude storm tracks are marked by regions frequented by baroclinic waves and their associated surface cyclones,” which bring with them “strong winds and heavy precipitation, seriously affecting regional weather and climate.”

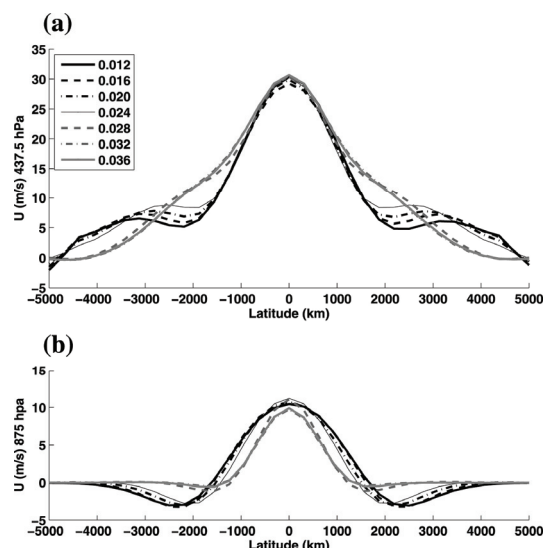


Figure 1.4.9.3. The latitudinal distribution of the zonal and time-averaged zonal winds at (a) 437.5 and (b) 875 hPa for a range of surface friction values. The latitude distance on the abscissa is in kilometers (0 km the channel center). Positive (negative) values are the distance poleward (equatorward). Reprinted with permission from Zhang, Y., Yang, X.Q., Nie, Y., and Chen, G. 2012. Annular mode-like variation in a multilayer quasigeostrophic model. *Journal of the Atmospheric Sciences* **69**: 2940–2958, Figure 3.

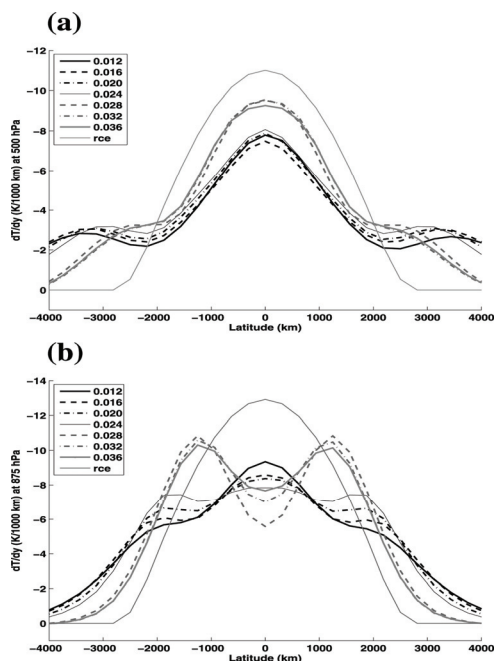


Figure 1.4.9.4. As in Figure 1.4.9.3, except for temperature gradients. Reprinted with permission from Zhang *et al.* (2012), Figure 4.

They also note such storms “transport large amounts of heat, momentum and moisture poleward,” making up “an important part of the global circulation,” and how these storm tracks may change as a result of global warming “is thus of huge societal interest.”

Chang *et al.* used “storm-track activity derived from ERA-Interim [European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala *et al.* 2005)] data as the current best estimate to assess how well models that participated in phase 3 of the Coupled Model Intercomparison Project (CMIP3; Meehl *et al.* 2007) that were considered in the Intergovernmental Panel on Climate Change *Fourth Assessment Report* (Solomon *et al.* 2007) do in simulating storm-track activity.”

The four researchers report “only 2 of the 17 models have both the Northern Hemisphere [NH] and Southern Hemisphere [SH] storm-track activity within 10% of that based on ERA-Interim” and “four models simulate storm tracks that are either both significantly (>20%) too strong or too weak.” They also note “the SH to NH ratio of storm-track activity ... is biased in some model simulations due to biases in midtropospheric temperature gradients” and “storm tracks in most CMIP3 models exhibit an equatorward bias in both hemispheres.” Further, “some models exhibit biases in the amplitude of the seasonal cycle”; “models having a strong (weak) bias in storm-track activity also have a strong (weak) bias in poleward eddy momentum and heat fluxes, suggesting that wave-mean flow interactions may not be accurately simulated by these models”; and “preliminary analyses of *Fifth Assessment Report* (AR5)/CMIP5 model data suggest that CMIP5 model simulations also exhibit somewhat similar behaviors.”

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1.4.10 Miscellaneous

Fu *et al.* (2011) note the *Fourth Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concluded climate projections based on models that consider both human and natural factors provide “credible quantitative estimates of future climate change.” However, they continue, mismatches between IPCC AR4 model ensembles and observations, especially the multidecadal variability (MDV), “have cast shadows on the confidence of the model-based decadal projections of future climate,” as also has been noted by Meehl *et al.*

(2009), who indicate considerably more work needs to be done in this important area.

In an exercise designed to illustrate the extent of this model failure, Fu *et al.* evaluated “many individual runs of AR4 models in the simulation of past global mean temperature,” focusing on the performance of individual runs of models included in the Coupled Model Intercomparison Project phase 3 (CMIP3) in simulating the multidecadal variability of the past global mean temperature.

The three researchers determined “most of the individual model runs fail to reproduce the MDV of past climate, which may have led to the overestimation of the projection of global warming for the next 40 years or so.” More specifically, they note simply taking into account the impact of the Atlantic Multi-decadal Oscillation shows “the global average temperature could level off during the 2020s–2040s,” such that the true temperature change between 2011 and 2050 “could be much smaller than the AR4 projection.”

Jeong *et al.* (2011) state “the Siberian High (SH) is the most conspicuous pressure system found in the Northern Hemisphere during wintertime,” when “strong radiative cooling over the snow covered Eurasian continent forms a cold-core high-pressure system in the lower troposphere over northern Mongolia” that exerts “tremendous influences on weather and climate in Northern Eurasia, East Asia, and even further into South Asia (e.g., Cohen *et al.*, 2001; Panagiotopoulos *et al.*, 2005; Wang, 2006).” The authors further state SH intensity variations—as simulated by 22 global climate models under 20C3M and A1B scenarios in the CMIP3—show “a steady decreasing trend in the SH intensity from the late 20th century throughout the 21st century, leading to a decrease of about 22% in SH intensity at the end of the 21st century compared to the 1958–1980 average.”

In a study designed to determine to what degree the temporal SH intensity simulations of these models mimic reality, Jeong *et al.* employed two observational gridded sea level pressure (SLP) data sets, that of the Hadley Centre and the National Centre for Atmospheric Research, plus two reanalysis data sets (NCEP and ERA40) and *in situ* SLP observations from 20 stations located in the central SH region to create a history of SH intensity over the past several decades.

The climatic reconstructive work of the seven scientists revealed “a pronounced declining trend of the SH intensity from the late 1960s to the early 1990s,” which would appear to mesh well with GCM

simulations presented in the IPCC AR4 that indicate a “steady weakening of the SH intensity for the entire 21st century.” The authors report, however, that in the real world the declining SH intensity trend “was sharply replaced by a fast recovery over the last two decades.” The thus note “this feature has not been successfully captured by the GCM simulations used for the IPCC AR4,” all of which predict “a steady decreasing trend in the SH intensity from the late 20th century throughout the 21st century.”

Jeong *et al.* conclude, “an improvement in predicting the future climate change in regional scale is desirable.”

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2

Forcings and Feedbacks

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Key Findings

Introduction

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- 2.1.1 Correlation with Temperature
- 2.1.2 Atmospheric Residence Time of CO₂

2.2 Methane

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- 2.2.2 Emissions to the Atmosphere
- 2.2.3 Extraction from the Atmosphere

2.3 Nitrous Oxide

2.4 Clouds

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- 2.4.2 Cloud Cover

2.5 Aerosols

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2.6 Other Forcings and Feedbacks

- 2.6.1 Carbon Sequestration
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Key Findings

The following points summarize the main findings of this chapter:

- Research published in peer-reviewed science journals indicates the model-derived temperature sensitivity of Earth accepted by the IPCC is too large. Negative feedbacks in the climate system reduce that sensitivity to values an order of magnitude smaller.
- Establishing the historic phase relationship

between atmospheric carbon dioxide and temperature is a necessary step toward understanding the physical relationship between CO₂ forcing and climate change. When such analyses are conducted, changes in CO₂ are frequently seen to *lag* changes in temperature by several hundred years.

- Many studies reveal a large *uncoupling* of temperature and CO₂ throughout portions of the historical record. Such findings contradict the IPCC's theory that changes in atmospheric CO₂

drive changes in temperature.

- Atmospheric methane observations over the past two decades reside far below the values projected by the IPCC in each of the four *Assessment Reports* it has released to date. The IPCC's temperature projections, which incorporate this inflated influence, should be revised downward to account for this discrepancy.
- Because agriculture accounts for almost half of nitrous oxide (N₂O) emissions in some countries, there is concern that enhanced plant growth due to CO₂ enrichment might increase the amount and warming effect of this greenhouse gas. But field research shows N₂O emissions will likely fall as CO₂ concentrations and temperatures rise, indicating this is actually another negative climate feedback.
- The IPCC has concluded "the net radiative feedback due to all cloud types is likely positive" (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, several studies indicate the net global effect of cloud feedbacks is a cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.
- The IPCC likely underestimates the total cooling effect of aerosols. Studies have found their radiative effect is comparable to or larger than the temperature forcing caused by all the increase in greenhouse gas concentrations recorded since preindustrial times.
- Higher temperatures are known to increase emissions of dimethyl sulfide (DMS) from the world's oceans, which increases the albedo of marine stratus clouds, which has a cooling effect. The IPCC characterizes this chain of events as "a rather weak aerosol-climate feedback at the global scale" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012), but many studies suggest otherwise.
- Several other important negative forcings and feedbacks exist in nature, about which little is known or acknowledged by the IPCC. Such forcings and feedbacks have been shown by multiple scientific studies to significantly

influence Earth's climate to a degree comparable to that of projected anthropogenic-induced global warming.

- The IPCC claims a positive feedback exists between climate and the carbon cycle on century to millennial time scales such that a warming climate will result in a loss of carbon storage. There is no empirical evidence to support such an assertion. Just the opposite appears to be the case, as global carbon uptake doubled over the past half-century.

Introduction

Scientists increasingly recognize climate is influenced not only by rising atmospheric carbon dioxide levels, but also other forcings and feedbacks. Even James Hansen—who in 1988 testified before a U.S. Senate Committee that "the global warming is now large enough that we can ascribe with a high degree of confidence a cause-and-effect relationship to the greenhouse effect"—was far more circumspect ten years later as lead author of a paper published in the *Proceedings of the National Academy of Sciences, U.S.A.* (Hansen *et al.*, 1998).

Hansen *et al.* examined the forcings of well-mixed greenhouse gases (CO₂, CH₄, N₂O, and CFCs), tropospheric ozone, stratospheric ozone, tropospheric aerosols, forced cloud changes, vegetation and other planetary surface alterations, solar variability, and volcanic aerosols. That examination revealed so many uncertainties in the forcings that the researchers concluded, "the forcings that drive long-term climate change are not known with an accuracy sufficient to define future climate change." Nevertheless, the IPCC has expressed confidence in projections of future climate, saying the temperature sensitivity of Earth's climate system in response to a doubling of atmospheric CO₂ concentrations "is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C [*italics in the original*]" (IPCC, 2007).

The preceding chapter discussed a host of biases and discrepancies that lessen confidence in the ability of models to project future climate. In Chapter 2, we now review important forcings and feedbacks in the climate system. Failure of the models to account properly for the influence of these forcings and feedbacks further erodes confidence in the model projections of climate. Some of the forcings and feedbacks discussed in this chapter may have the potential to offset completely the radiative forcing

expected from rising atmospheric CO₂.

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2.1 Carbon Dioxide

When Earth was in its infancy, some 4.5 billion years ago, the atmosphere was predominantly composed of carbon dioxide. At that time, its CO₂ concentration, in terms of the units most commonly used today, would have been at something on the order of 1,000,000 ppm. Ever since, however, the CO₂ content of the air, in the mean, has been dropping.

By 500 million years ago, it is estimated the atmosphere's CO₂ concentration fell to a value of only ~20 times more than it is today, around 7,500 ppm. By 300 million years ago it had declined to close to the air's current CO₂ concentration of 400 ppm, after which it rose to four times that amount at 220 million years before present (Berner 1990, 1992, 1993, 1997; Kasting 1993). During the middle Eocene, some 43 million years ago, the atmospheric CO₂ concentration is estimated to have dropped to a mean value of approximately 385 ppm (Pearson and Palmer, 1999), and between 25 million and 9 million years ago, it is believed to have varied between 180 and 290 ppm (Pagani *et al.*, 1999). This last range is essentially the same range over which the air's CO₂ concentration oscillated during the 100,000-year glacial cycles of the past 420,000 years (Fischer *et al.*, 1999; Petit *et al.*, 1999). With the inception of the Industrial Revolution, the air's CO₂ content has surged upward, now above 400 ppm with the promise of significantly higher concentrations to come.

In addition to its variation over geologic time, the atmosphere's CO₂ concentration exhibits a seasonal variation. It declines when terrestrial vegetation awakens from the dormancy of winter and begins to grow in the spring, thereby extracting great quantities

of CO₂ from the air; and it rises in the fall and winter, when much of the biomass produced over the summer dies and decomposes, releasing great quantities of CO₂ back to the atmosphere.

The air's CO₂ content also varies spatially over the surface of Earth. Most spectacular in this regard are the local concentration enhancements observed over large metropolitan areas due to high levels of vehicular traffic and commercial activities. Idso *et al.* (1998a, b), for example, measured CO₂ concentrations near the center of Phoenix, Arizona that were 50 percent greater than those measured over surrounding rural areas. Significant enhancements of the air's CO₂ concentration also may be observed in the vicinity of burning coal seams and naturally occurring high-CO₂ springs.

Given the radiative properties of atmospheric CO₂, concerns have been expressed for some time that rising levels of CO₂ may lead to a significant warming of the planet. The IPCC supports such a hypothesis of future CO₂-induced climate change, and it also has concluded the modern rise of atmospheric CO₂ is affecting the climate *now*. Writing in its *Fifth Assessment Report* (FAR), the IPCC states

Globally, CO₂ is the strongest driver of climate change compared to other changes in the atmospheric composition, and changes in surface conditions [since the Industrial Revolution]. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers. CO₂ concentrations and rates of increase are unprecedented in the last 800,000 years and at least 20,000 years, respectively (Summary for Policy Makers, Second Order Draft of AR5, October 5, 2012, p. 7).

Research suggests, however, that the IPCC's view of atmospheric CO₂ as "the strongest driver of climate change" should be reconsidered if not outright rejected. The studies reviewed here find it is likely rising atmospheric CO₂ concentrations will have little impact on future climate.

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2.1.1 Correlation with Temperature

According to the IPCC, the global warming of the mid- to late twentieth century and early twenty-first century was caused primarily by the rise in atmospheric CO₂ concentration. This assertion is controversial (see Smagorinsky *et al.* (1982) and Idso (1982) for early pro/con positions on the issue), and with the retrieval and preliminary analysis of the first long ice core from Vostok, Antarctica—which provided a 150,000-year history of both surface air temperature and atmospheric CO₂ concentration—the debate became even more intense. The close associations of the ups and downs of atmospheric CO₂ and temperature evident during glacial terminations and inceptions in that record, as well as in subsequent records of even greater length, led many supporters of

the CO₂-induced global warming theory to assert those observations proved anthropogenic CO₂ emissions were responsible for twentieth century global warming.

This contention was challenged by Idso (1989), who wrote, “changes in atmospheric CO₂ content never precede changes in air temperature, when going from glacial to interglacial conditions; and when going from interglacial to glacial conditions, the change in CO₂ concentration actually lags the change in air temperature (Genthon *et al.*, 1987).” He thus concludes, “changes in CO₂ concentration cannot be claimed to be the cause of changes in air temperature, for the appropriate sequence of events (temperature change following CO₂ change) is not only never present, it is actually violated in [at least] half of the record (Idso, 1988).”

The following subsections expand on such research. Our understanding of the relationship between atmospheric CO₂ and temperature has improved in the years since, clearly demonstrating the lack of a causal link.

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2.1.1.1 Geologic Epochs

Rothman (2002) derived a 500-million-year history of the air's CO₂ content based on considerations related to the chemical weathering of rocks, volcanic and metamorphic degassing, and the burial of organic carbon, along with considerations of the isotopic content of organic carbon and strontium in marine

sedimentary rocks. This analysis suggests over the majority of the half-billion-year record, Earth's atmospheric CO₂ concentration fluctuated between values two to four times greater than those of today at a dominant period on the order of 100 million years (see Figure 2.1.1.1.1). Over the past 175 million years, however, the data depict a long-term decline in the air's CO₂ content.

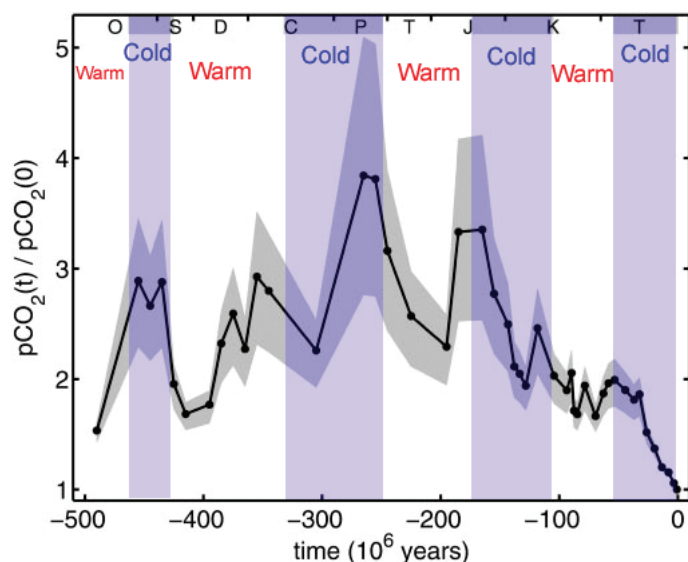


Figure 2.1.1.1.1. A 500-million-year record of the atmosphere's CO₂ concentration (relative to that of the present = 1) together with indications of periods of relative cold and warmth. Adapted from Rothman, D.H. 2002. Atmospheric carbon dioxide levels for the last 500 million years. *Proceedings of the National Academy of Sciences USA* **99**: 4167–4171.

With respect to the question of what correspondence might exist between ancient climates and atmospheric CO₂ concentrations, Rothman states the CO₂ history of Figure 2.1.1.1.1 “exhibits no systematic correspondence with the geologic record of climatic variations at tectonic time scales.” A visual examination of Rothman's plot of CO₂ and concomitant major cold and warm periods clearly indicates the three most striking peaks in the air's CO₂ concentration occur either totally or partially within periods of time when Earth's climate was relatively cool. Not only is there no support in these data for the claim that high atmospheric CO₂ concentrations tend to warm the planet, the data suggest there are times in Earth's history when just the opposite was the case.

Focusing on the middle Eocene climate of 43 million years ago, Pearson and Palmer (1999) report the planet then may have been as much as 5°C warmer than today, yet the mean CO₂ concentration of the atmosphere, as determined by pH data inferred from boron isotope composition in planktonic foraminifera, was only about 385 ppm.

Much the same was found by these authors one year later in an analysis of atmospheric CO₂ and temperature over the past 60 million years (Pearson and Palmer, 2000). Sixty million years before present (BP), the authors note, the atmosphere's CO₂ concentration, shown at the left in Figure 2.1.1.1.2, was approximately 3,600 ppm and the oxygen isotope ratio (at the right in the figure) was about 0.3 per mil (Figure 2.1.1.1.2, orange highlight). Thirteen million years later, the air's CO₂ concentration had dropped to 500 ppm, yet the oxygen isotope ratio dropped (implying a rise in temperature) to zero. That is just the opposite of what one would expect were CO₂ the driver of climate change.

Next comes a large spike in the air's CO₂ content, all the way up to a value of 2,400 ppm (Figure 2.1.1.1.2, blue). What does the oxygen isotope ratio do at that time? It rises slightly (implying the temperature falls slightly) to about 0.4 per mil, again just the opposite of what one would expect under the CO₂-induced global warming hypothesis.

After the spike in CO₂, the air's CO₂ concentration drops dramatically, declining to a minimum value of close to what it is today (Figure 2.1.1.1.2, purple). The oxygen isotope ratio barely changes at all, defying once again the assumption of the CO₂-induced global warming hypothesis.

Between this point and the break in the record at 40 million years BP, the air's CO₂ concentration rises again to approximately 1,000 ppm, and the oxygen isotope ratio rises slightly (implying a slight cooling) to 0.6 per mil (Figure 2.1.1.1.2, blue). Again, the common assumption of the CO₂-induced global warming hypothesis—that changes in atmospheric CO₂ drive changes in air temperature—fails.

Picking up the record at 24 million years BP, there are relatively tiny variations in atmospheric CO₂ concentration up to the present but large variations in oxygen isotope values, both up and down, again in clear contradiction of the CO₂-induced global warming hypothesis (Figure 2.1.1.1.2, yellow). The most interesting of these oxygen isotope changes is the dramatic increase (implying a dramatic cooling) over the most recent two million years, when the air's

Climate Change Reconsidered II

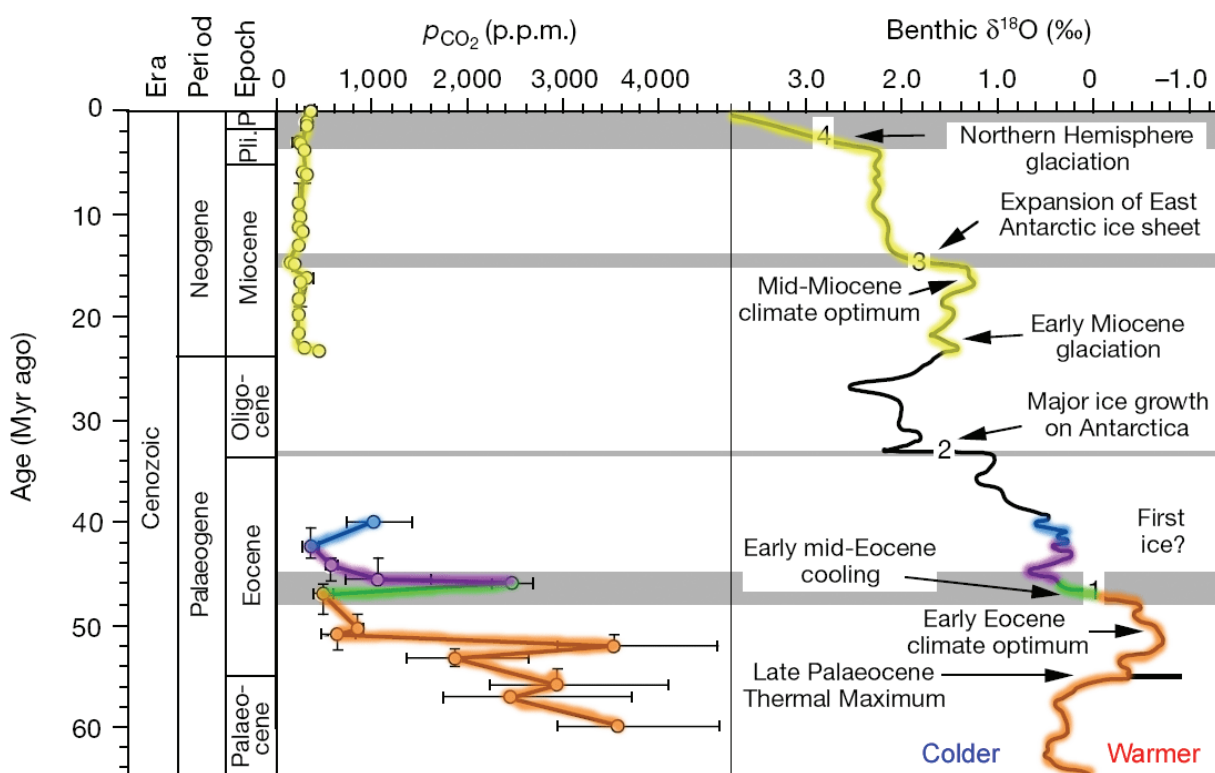


Figure 2.1.1.1.2. Atmospheric CO₂ concentration and proxy temperature over the past 60 million years. Adapted from Pearson, P.N. and Palmer, M.R. 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature* 406: 695–699.

CO₂ concentration has risen slightly.

In another detailed review of Earth's thermal and CO₂ history, Pagani *et al.* (2005) examined these parameters over the most recent 50 million years. Their examination revealed essentially the same findings as the study of Pearson and Palmer (2000). As demonstrated in Figure 2.1.1.1.3, about 43 million years ago the atmosphere's CO₂ concentration was approximately 1,400 ppm and the oxygen isotope ratio (a proxy for temperature) was about 1.0 per mil. Then, over the next ten million years, the air's CO₂ concentration underwent three huge oscillations on the order of 1,000 ppm from peak to valley (Figure 2.1.1.1.3, red). In the first two oscillations, temperature appeared not to respond at all, exhibiting an uninterrupted slow decline represented by the steady upward trend in δ¹⁸O. Following the third rise in CO₂, however, temperatures seemed to respond, but in the opposite direction to what is expected according to the CO₂-induced global warming hypothesis—the rise in CO₂ was followed by the sharpest drop in temperature (rise in δ¹⁸O) of the entire record.

Following this large drop in temperature between 34 and 33 million years before present (Ma BP), the oxygen isotope ratio hovered around a value of 2.7 per mil from about 33 to 26 Ma BP, indicating little change in temperature over that period. The corresponding CO₂ concentration (Figure 2.1.1.1.3, green) was anything but constant, experiencing about a 500 ppm increase around 32 Ma BP, after which it dropped a full 1,000 ppm over the next two million years, only to rise again by a few hundred ppm, repeatedly defying the common causal assumption of the CO₂-induced global warming hypothesis.

Around 26 Ma BP, the oxygen isotope ratio dropped to about 1.4 per mil (implying a significant rise in temperature), during which time the air's CO₂ content (Figure 2.1.1.1.3, yellow) declined, once again the opposite of what one would expect were CO₂ driving climate change. Then, from 24 Ma BP to the end of the record at 5 Ma BP, there were relatively tiny variations in the atmosphere's CO₂ content (Figure 2.1.1.1.3, blue) but large variations in oxygen isotope values, both up and down.

Forcings and Feedbacks

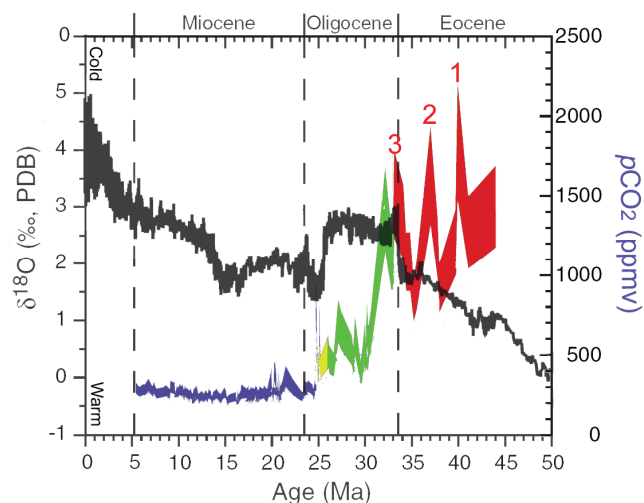


Figure 2.1.1.1.3. Atmospheric CO₂ concentration (multicolored line) and proxy temperature (black line) over the past 50 million years. Adapted from Pagani, M., Zachos, J.C., Freeman, K.H., Tipple, B., and Bohaty, S. 2005. Marked decline in atmospheric carbon dioxide concentrations during the Paleogene. *Science* **309**: 600–603.

These observations, according to Pagani *et al.* (2005), “argue for a decoupling between global climate and CO₂” and stand in clear contradiction of the CO₂-induced global warming hypothesis.

Pagani *et al.* (1999), working with sediment cores from three deep-sea drilling sites, also found the air’s CO₂ concentration to be uniformly low (180 to 290 ppm) throughout the early to late Miocene (25 to 9 million years ago), at a time when deep-water and high-latitude surface water temperatures were as much as 6°C warmer than today. They stated their finding “appears in conflict with greenhouse theories of climate change.” In addition, they noted the air’s CO₂ concentration seemed to rise after the expansion of the East Antarctic Ice Sheet, also in conflict with greenhouse theories of climate change.

Considered in their entirety, the results of these studies present a truly chaotic picture with respect to any possible effect variations in atmospheric CO₂ concentration may have on global temperature. The IPCC has neglected to adequately address the inconsistency between these real-world observations and the model-based projections in their reports.

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2.1.1.2 Pleistocene Glacial/Interglacial Cycles

Several studies have shed additional light on the relationship between CO₂ and temperature as manifested throughout the past 800,000 years of dramatic glacial-interglacial climate cycles.

Fischer *et al.* (1999), for example, examined trends of atmospheric CO₂ and air temperature derived from Antarctic ice core data extending back 250,000 years. Over this period, the three most dramatic warming events experienced on Earth were the terminations of the last three ice ages; for each of these climatic transitions, Earth’s air temperature always rose well in advance of the increase in atmospheric CO₂. In each transition, the air’s CO₂ content did not begin to rise until 400 to 1,000 years after the planet began to warm.

Another team to study the CO₂-temperature relationship was that of Petit *et al.* (1999), who discovered during all glacial inception of the past half-million years, temperature always dropped well before the decline in the air’s CO₂ concentration. They conclude their data indicate “the CO₂ decrease lags the temperature decrease by several thousand years.” Likewise, Mudelsee (2001) determined variations in atmospheric CO₂ concentration lagged behind variations in air temperature by 1,300 to 5,000 years over the past 420,000 years. In addition, during certain climatic transitions characterized by rapid warmings of several degrees, which were followed by slower coolings that returned the climate to

essentially full glacial conditions, Stauffer *et al.* (1998) observe the atmospheric CO₂ concentration derived from ice core records typically varied by less than 10 ppm. They, too, consider the CO₂ perturbations to have been caused by the changes in climate, rather than vice versa.

Many other studies have demonstrated this reverse coupling of atmospheric CO₂ and temperature (Cheddadi *et al.*, 1998; Gagan *et al.*, 1998; Raymo *et al.*, 1998), where temperature is the independent variable that appears to induce changes in CO₂. In addition, Steig (1999) noted cases of the inverse coupling of the two parameters, showing between 7,000 and 5,000 years ago, atmospheric CO₂ concentrations increased by just over 10 ppm at a time when temperatures in both hemispheres cooled.

Caillon *et al.* (2003) measured the isotopic composition of argon—specifically, $\delta^{40}\text{Ar}$, which they argued “can be taken as a climate proxy, thus providing constraints about the timing of CO₂ and climate change”—in air bubbles in the Vostok ice core over the period that comprises what is called Glacial Termination III, about 240,000 years ago. The results of their meticulous analysis led them to conclude “the CO₂ increase lagged Antarctic deglacial warming by 800 ± 200 years” (see Figure 2.1.1.2.1)

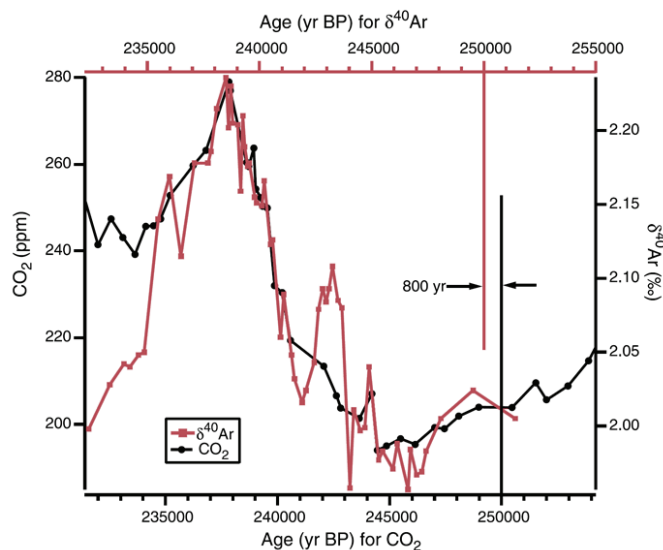


Figure 2.1.1.2.1. Isotopic argon and CO₂ values from Vostok Ice core air bubbles. Note the 800 year offset between the top ($\delta^{40}\text{Ar}$) and bottom (CO₂) axes for Age (yr BP). Reprinted with permission from Caillon, N., Severinghaus, J.P., Jouzel, J., Barnola, J.-M., Kang, J., and Lipenkov, V.Y. 2003. Timing of atmospheric CO₂ and Antarctic temperature changes across Termination III. *Science* **299**: 1728–1731.

This finding, in the words of Caillon *et al.*, “confirms that CO₂ is not the forcing that initially drives the climatic system during a deglaciation.” Nevertheless, they and others continue to hold the view that the subsequent increase in atmospheric CO₂—believed to be due to warming-induced CO₂ outgassing from the world’s oceans—serves to amplify the warming caused by whatever prompts the temperature to rise in the first place. This supposition is founded on unproven assumptions about the strength of CO₂-induced warming and is applied without any regard for biologically induced negative climate feedbacks that may occur in response to atmospheric CO₂ enrichment, as discussed later in this chapter. Moreover, there is no way to objectively determine the strength of the proposed amplification from the ice core data.

In light of these observations, the role of CO₂ as a primary driver of climate change on Earth would appear to be disproved; the CO₂ warming amplification hypothesis appears unlikely as well.

Another departure from standard greenhouse effect theory occurred over the 17,000-year period following the penultimate deglaciation, when the air’s CO₂ content was essentially constant but air temperature declined to values characteristic of glacial times (see Figure 2.1.1.2.2). An even greater contradiction of IPCC-based thinking occurred immediately thereafter, when CO₂ finally began to fall but temperature began to rise.

Also discovering an inverse greenhouse gas/temperature relationship were Indermuhle *et al.* (1999), who determined after the termination of the last great ice age the CO₂ content of the air gradually rose by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, over a period of slow but steady decline in global air temperature. A year later, working with a high-resolution temperature and atmospheric CO₂ record spanning the period 60 to 20 thousand years ago, Indermuhle *et al.* (2000) discovered four distinct periods when temperatures rose by approximately 2°C and CO₂ rose by about 20 ppm. One of the statistical tests they performed on the data suggests the shifts in the air’s CO₂ content during these intervals *followed* the shifts in air temperature by approximately 900 years, and a second statistical test yielded a mean CO₂ lag time of 1,200 years.

Another pertinent study comes from Siegenthaler *et al.* (2005), who analyzed CO₂ and temperature proxy (δD , the ratio of deuterium to hydrogen) data derived from an ice core in Antarctica. Results of

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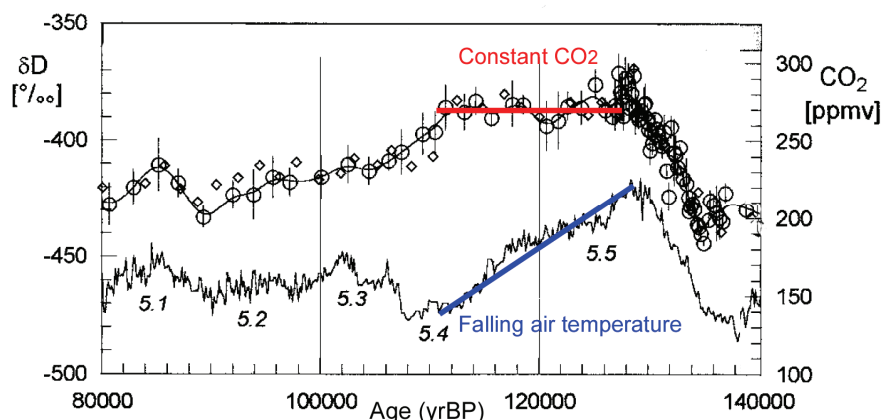


Figure 2.1.1.2.2. Atmospheric CO₂ and proxy temperature. Adapted from Fischer, H., Wahlen, M., Smith, J., Mastroianni, D., and Deck, B. 1999. Ice core records of atmospheric CO₂ around the last three glacial terminations. *Science* **283**: 1712–1714..

their analysis revealed a coupling of Antarctic temperature and CO₂ in which they obtained the best correlation between CO₂ and temperature “for a lag of CO₂ of 1900 years.” Over the course of glacial terminations V to VII, they observe “the highest correlation of CO₂ and deuterium, with use of a 20-ky window for each termination, yields a lag of CO₂ to deuterium of 800, 1600, and 2800 years, respectively.” In addition, they note “this value is consistent with estimates based on data from the past four glacial cycles,” citing the work of Fischer *et al.* (1999), Monnin *et al.* (2001), and Caillon *et al.* (2003). This too confirms temperature leads this tightly coupled relationship, while CO₂ lags, possibly providing only a fraction (which could well be miniscule) of the total glacial-to-interglacial temperature change.

Such observations do little to inspire confidence in projections that the CO₂ produced by the burning of fossil fuels will lead to significant global warming, where predicted warmings in some scenarios rival those experienced in glacial-to-interglacial transitions. Nevertheless, Siegenthaler *et al.* maintained the new findings “do not cast doubt ... on the importance of CO₂ as a key amplification factor of the large observed temperature variations of glacial cycles.” However, it should be noted that when temperature leads CO₂ by thousands of years, during both glacial terminations and inception (Gentson *et al.*, 1987; Fischer *et al.*, 1999; Petit *et al.*, 1999; Indermuhle *et al.*, 2000; Monnin *et al.*, 2001; Mudelsee, 2001; Caillon *et al.*, 2003), there is ample reason to conclude CO₂ plays but a minor role in enhancing

temperature changes that are clearly induced by something else.

Thomas Stocker (the second and corresponding author of the Siegenthaler *et al.* paper) was quoted by the BBC’s Richard Black (BBC News, 24 Nov 2005) as saying the relationship they observed between δD and CO₂ is “a very strong indication of the important role of CO₂ in climate regulation.” A more plausible statement, however, would be that the relationship is “a very strong indication of the important role of climate in CO₂ regulation.” As evidenced by 650,000 years of real-world data, wherever temperature went over this period, CO₂ (mostly)

followed.

Still other papers have chipped away at the IPCC-led hypothesis that atmospheric CO₂ is and will be the dominant driver of climate change both now and in the future.

Kirchner (2002) present a pair of interesting graphs, the first of which is a plot of temperature vs. atmospheric CO₂ concentration he derived from 400,000 years of Vostok ice core data, adapted as Figure 2.1.1.2.3. The plot in this graphic displays a fair amount of scatter but seems to suggest the existence of a crude linear relationship between the two variables, which is what Kirchner implied by drawing a best-fit linear regression line through the data (the solid dark red line).

However, the data may be equally well characterized as a two-dimensional distribution, such as that shown in Figure 2.1.1.2.4. The apex is anchored at the point defined by the coldest temperature and lowest CO₂ concentration of the data set. Rather than a crude linear relationship between temperature and CO₂, this “slice of pie” characterization may be preferred, for when the current temperature–CO₂ state of the world is plotted, it falls far below the linear relationship derived by Kirchner but right on the lower side of the piece of pie we would place over the data.

With respect to the meaning of the plotted relationship, Kirchner notes “despite greenhouse gas concentrations that are unprecedented in recent Earth

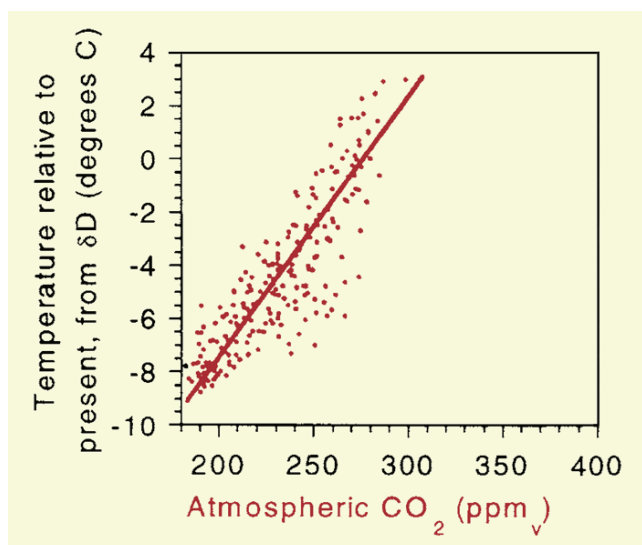


Figure 2.1.1.2.3. Scatter-plot of Vostok ice core-derived atmospheric CO₂ and proxy temperature data over the last 400,000 years. Adapted from Kirchner, J.W. 2002. The Gaia Hypothesis: fact, theory, and wishful thinking. *Climatic Change* 52: 391–408..

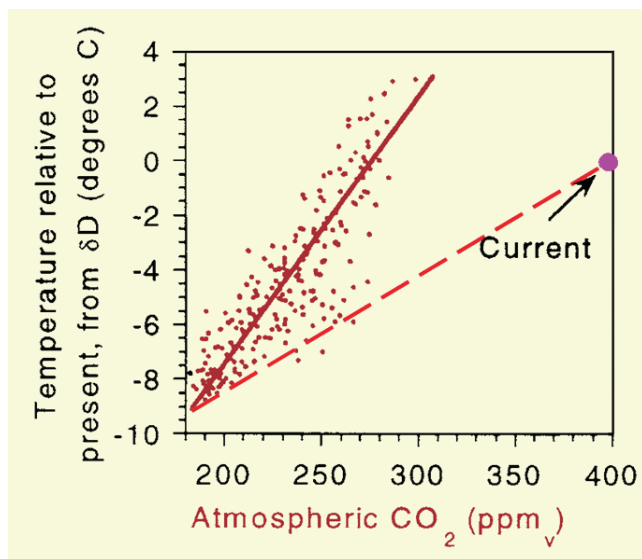


Figure 2.1.1.2.4. Adapted from Kirchner 2002, same as Figure 2.1.1.2.3, but with the current CO₂ concentration of the atmosphere and the dashed red line added.

history, global temperatures have not (yet) risen nearly as much as the correlations in the ice core records would indicate that they could.” He pointed out, for example, that his representation of the ice core data suggests “for the current composition of the atmosphere, current temperatures are anomalously cool by many degrees.” Kirchner’s work suggests the

anomaly is approximately 10°C, significantly more than the maximum warming currently predicted by the Intergovernmental Panel on Climate Change to accompany a doubling of the air’s CO₂ content. One might also say the data as depicted in Figure 2.1.1.2.4 suggests Earth’s current temperature is not “anomalous” at all.

Kirchner’s second graph (not shown), a plot of temperature vs. atmospheric methane concentration, is also of interest. The relationship described by the data is absolutely and unquestionably linear and exhibits very little scatter. When used to compute what the temperature of today’s Earth “should be,” on the basis of the current atmospheric methane concentration, the result is fully 40°C more than the planet’s current temperature. This graphic too provides no basis for characterizing Earth’s current temperature as anomalous. Instead, in both the case of methane and of CO₂, it is the atmospheric greenhouse gas concentration that is anomalous.

Since Kirchner’s temperature vs. atmospheric methane concentration plot reveals such a tight coupling of temperature and methane, but the relationship between the two is such that methane cannot be the determinant of temperature, it must be concluded that temperature is the determinant of atmospheric methane concentration ... as long as humanity is not a part of the picture.

For nearly all of the past 400,000 years, this restriction has applied. As humanity’s population and impact on the biosphere have grown over the past few centuries, however, this relationship has been outgrown, causing the atmosphere’s methane concentration to rise to levels far above anything experienced throughout the history of the Vostok ice core. But Earth’s temperature has not responded to the anthropogenic-induced methane increase and is currently about 3°C cooler than it was during the peak warmth of the prior 400,000 years (Figure 2.1.1.2.5), when the air’s methane concentration was only 40 percent of what it is today.

A similar conclusion can be reached about temperature and atmospheric CO₂ concentration: It is temperature change that elicits changes in the air’s CO₂ content and not vice versa, although the scatter in Kirchner’s temperature vs. atmospheric CO₂ concentration plot is sufficient to allow for significant independent movement by both of these parameters. The conclusion that atmospheric CO₂ concentration is not a major determinant of Earth’s temperature is supported by the fact that Earth is currently about 3°C cooler than it was during the peak warmth of the prior

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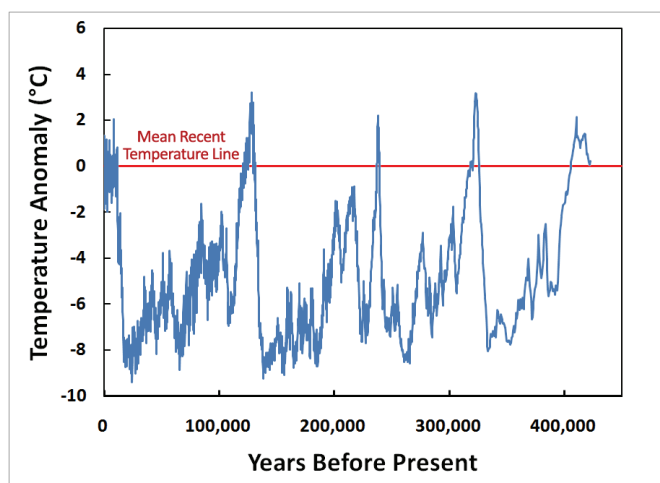


Figure 2.1.1.2.5. Proxy temperatures going back 420,000 years, based on tabular data presented in Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., 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.

four interglacials, when the air's CO₂ content was only about 75 percent of what it is today.

When considering the above observations together, the findings are remarkable. Since the occurrence of the peak temperature of the past 400,000 years, the concentrations of the two most powerful greenhouse gases in the atmosphere (exclusive of water vapor)—CO₂ and methane—have increased by approximately a third and 2.5-fold, respectively, yet Earth's temperature has fallen by 3°C. Clearly, CO₂ and methane are not the important drivers of climate change the IPCC and others consider them to be.

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2.1.1.3 Holocene

Several researchers have examined the relationship between atmospheric CO₂ and temperature during the transition from the glacial conditions of the last ice age to the interglacial conditions of the present Holocene. As in the studies examined in the preceding two sections, their data reveal a number of problems with the IPCC-based hypothesis that rising CO₂ will cause unprecedented warming of the planet.

Focusing on the period between 22,000 and 9,000 years ago, Monnin *et al.* (2001) found the start of the CO₂ increase lagged the start of the temperature increase by 800 years. An analysis of this most recent glacial/interglacial transition by Yokoyama *et al.* (2000), which also has been discussed by Clark and Mix (2000), revealed a rapid rise in sea level, caused by the melting of land-based ice that began approximately 19,000 years ago, preceded the post-glacial rise in atmospheric CO₂ concentration by about 3,000 years. Only after a couple thousand years did CO₂ concentration catch up with the sea level rise.

Stott *et al.* (2007) state establishing “the exact phasing of events during glacial terminations” is “a necessary step in understanding the physical relation between CO₂ forcing and climate change.” Working with a marine sediment core from the western tropical Pacific Ocean, Stott *et al.* set out to determine “the chronology of high- and low-latitude climate change at the last glacial termination by radiocarbon dating benthic and planktonic foraminiferal stable isotope and magnesium/calcium records.” This provided a temporal resolution of 25 to 50 years for each sample over the period stretching from 10 thousand to 22 thousand years before the present. The research team found “deep-sea temperatures warmed by ~2°C between 19 and 17 thousand years before the present, leading the rise in atmospheric CO₂ and tropical-surface-ocean warming by ~1000 years.”

Stott *et al.* conclude the cause of the deglacial deep-water warming “does not lie within the tropics, nor can its early onset between 19 and 17 thousand years before the present be attributed to CO₂ forcing.” And since the rate of deep-water warming did not increase after the start of the increase in the atmosphere’s CO₂ concentration (if anything, it

declined), there is no compelling reason to infer the deglacial increase in the air’s CO₂ content had anything to do with the warming that led to the ultimate development of the current interglacial.

Working in Africa, Tierney *et al.* (2008) report the initiation of the deglacial warming in southeast Africa “is consistent with rising temperatures at ~20,000 years B.P. in Antarctica,” but they add the deglacial warming “leads the deglacial CO₂ rise recorded in Antarctic ice cores by about 3,000 years.” They describe this as “a difference that is outside the chronological errors of the ice core and the lake surface temperature records.” Tierney *et al.* conclude “increasing greenhouse gas concentrations are therefore not responsible for the initial transmission of warming from the high latitudes to the southeast African tropics.”

McElwain *et al.* (2002) derived high-resolution (approximately 20- to 37-year accuracy) atmospheric CO₂ histories from stomatal frequencies measured on subfossil leaves of *Dryas integrifolia*, *Picea mariana*, *P. glauca*, and *Larix laricina* obtained from sediment cores extracted from two sites in New Brunswick, Canada that contained material spanning the period from approximately 13,000 to 10,500 years ago. Their data reveal an abrupt drop in atmospheric CO₂ concentration of approximately 75 ppm at the onset of the Younger Dryas cold event. This drop in CO₂ lagged the event-defining temperature drop by approximately 130 years. Then, at the end of the Younger Dryas, there was a rapid rise in atmospheric CO₂ concentration that was (within the time-resolution error bounds of the data) essentially coeval with the increase in temperature that brought an end to the Younger Dryas and initiated the Holocene. In absolute terms, the pre-Younger Dryas CO₂ concentration was approximately 300 to 320 ppm, the concentration during the Younger Dryas interval approximately 235 ppm, and the concentration immediately afterwards in the range of 285 to 300 ppm.

Comparing their results with atmospheric CO₂ concentrations derived from polar ice core data, the authors note the best such data available had time resolutions of approximately 200 to 550 years. Degrading (averaging) their data accordingly, they were able to closely match the ice core results, a steady increase in atmospheric CO₂ concentration from the beginning to the end of the Younger Dryas interval. But the ice core data could not mimic the much-finer-scale story told by their data, including the dramatic decline in atmospheric CO₂

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concentration at the inception of the Younger Dryas and the dramatic increase in the air's CO₂ content at the conclusion of the cold event.

That the decline in atmospheric CO₂ concentration at the onset of the Younger Dryas lagged the decline in temperature by some 130 years clearly demonstrates the change in the air's CO₂ content did not cause the change in temperature, but that the temperature drop—or whatever caused it—was responsible for the decline in CO₂ concentration. There is little reason to believe the same was not true at the end of the Younger Dryas, although the authors' data resolution was not good enough to explicitly demonstrate that fact.

Other studies have demonstrated a complete uncoupling of CO₂ and temperature (Cheddadi *et al.*, 1998; Gagan *et al.*, 1998; Raymo *et al.*, 1998). Indermuhle *et al.* (1999) demonstrated after the termination of the last great ice age, the CO₂ content of the air gradually rose by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, during a period of time that manifested a slow but steady decline in mean global air temperature. Steig (1999) found between 7,000 and 5,000 years ago, atmospheric CO₂ concentrations increased by just over 10 ppm while temperatures in both hemispheres cooled. These results are just the opposite of what would be expected if changes in

atmospheric CO₂ drove climate change as claimed by the CO₂ greenhouse effect theory.

The case for an uncoupling of CO₂ and temperature is driven home further by an examination of the long-term temperature record produced by the Greenland Ice Sheet Project (GISP2), depicted in Figure 2.1.1.3.1 as plotted by Drake (2012) and based on data reported by Alley (2004).

It is most interesting to note that over its first 4,800 years (fully 96 percent of the record), when temperature varied widely, the atmosphere's CO₂ concentration was extremely stable, between about 275 and 285 ppm, whereas over the past 200 years (the remaining 4 percent of the record), when the temperature shows but a fraction of a degree warming, the air's CO₂ concentration rose by more than an extra 100 ppm.

Although almost any long-term temperature history could be used to make this point, it is clear from this simple example that the air's CO₂ content is not a major driver of Earth's temperature. It may not even be a minor driver, and it may have even less of an effect on climate in the not-so-distant future as the population of the world reaches a peak.

Consider, for example, the work of Idso (1989), who derived a predictive relationship based on world population and atmospheric CO₂ concentration data, updated and presented here as Figure 2.1.1.3.2. The

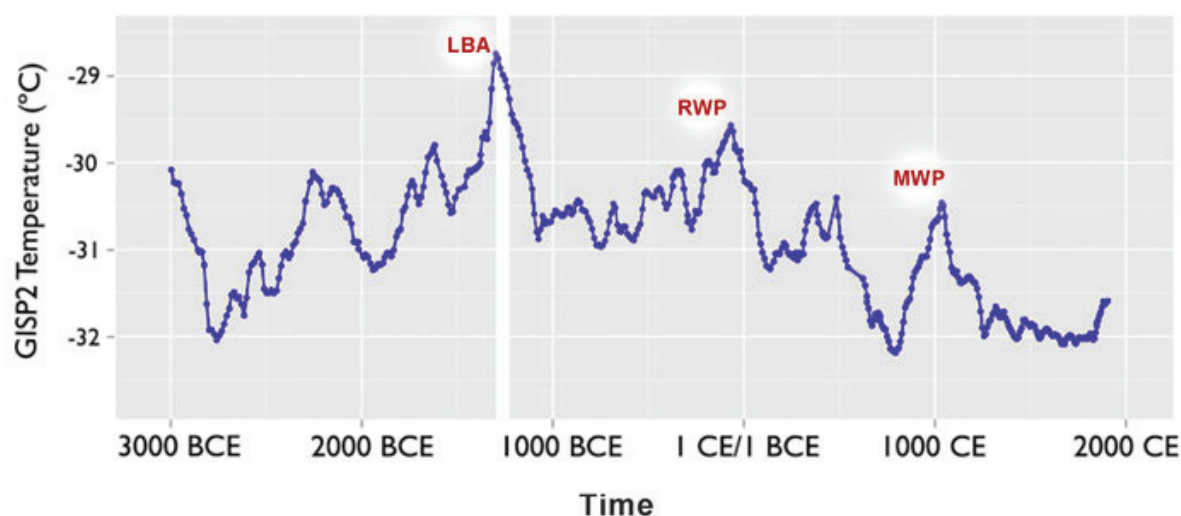


Figure 2.1.1.3.1. The past 5,000 years of the GISP2 temperature history of the Greenland Ice Sheet with general locations of the Late Bronze Age (LBA), the Roman Warm Period (RWP), and the Medieval Warm Period (MWP) indicated. Adapted from Drake, B.L. 2012. The influence of climatic change on the Late Bronze Age Collapse and the Greek Dark Ages. *Journal of Archaeological Science* 39: 1862–1870.

figure depicts a linear relationship between global population (an alternative representation of CO₂ emissions) and atmospheric CO₂ concentration, a relationship that has endured over time in spite of ongoing and sometimes rapid changes in energy sources and the energy mix as society has industrialized and modernized. That this relationship has remained steady over time is remarkable.

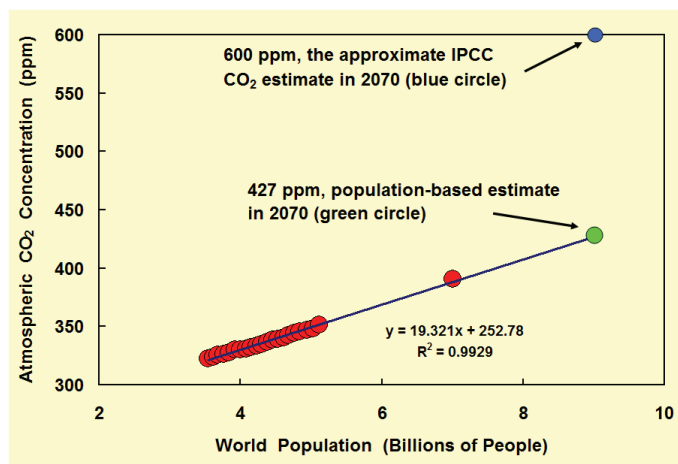


Figure 2.1.1.3.2. Atmospheric CO₂ concentration vs. world population based on data presented by Idso (1989), updated to 2011, the year Earth's population reached the seven billion mark. The linear regression line has been extrapolated to a population of nine billion persons. The IPCC-based projected CO₂ concentration in 2050 is also presented (blue circle). See Idso, S.B. 1989. *Carbon Dioxide and Global Change: Earth in Transition*. Tempe AZ: IBR Press.

The original linear relationship has been extended here to a world population of nine billion people, which is where Lutz *et al.* (2001) calculate the population of the planet will peak in the year 2070, according to the median result of their several projections. At this population, using the linear regression relationship depicted, an atmospheric CO₂ concentration of 427 ppm is calculated. Beyond this point in time, the peak in global population, the relationship suggests atmospheric CO₂ levels may level off and begin to drop as the planet's population stabilizes and/or begins to decline.

Such a conclusion is dramatically at odds with the IPCC projections, which predict far greater CO₂ concentrations for far greater times to come, but is likely far more robust. The equation derived in the above figure, for example, is based on data since

1650. For the past three-and-a-half centuries it has performed marvelously, including over the period of dramatic global population growth, during large changes in both the global source and mix of energy, and over the period of rapid growth in anthropogenic CO₂ emissions that occurred after World War II, suggesting this relationship will not suddenly cease to apply over the next six decades when the planet's population peaks. Although there may be slight variations ahead, they likely will be so small as to be essentially insignificant.

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2.1.2 Atmospheric Residence Time of CO₂

In a paper published in the international peer-reviewed journal *Energy & Fuels*, Dr. Robert H. Essenhigh, professor of energy conversion at The Ohio State University, addressed the residence time (RT) of anthropogenic CO₂ in the air. Essenhigh (2009) notes the IPCC in its first report (Houghton *et al.*, 1990) gave an atmospheric CO₂ residence time (lifetime) of 50 to 200 years as a “rough estimate.” That estimate is confusingly presented as an adjustment time for a scenario with a given anthropogenic CO₂ input, and it ignores natural (sea and vegetation) CO₂ flux rates. Such estimates are analytically invalid and in conflict with the more correct explanation given elsewhere in the same IPCC report: “This means that on average it takes only a few years before a CO₂ molecule in the atmosphere is taken up by plants or dissolved in the ocean.”

Some 99 percent of the atmospheric CO₂ molecules are ¹²CO₂ molecules containing the stable isotope ¹²C (Segalstad, 1982). To calculate the RT of ¹²CO₂, Essenhigh used the 1990 IPCC data with 750 gigatons total mass atmospheric carbon and a natural input/output exchange rate of 150 gigatons of carbon per year (Houghton *et al.*, 1990). The characteristic decay time (denoted by the Greek letter tau) is the former value divided by the latter value: 750 / 150 = five years. This is similar to the ~5 years found from mass balance calculations of measured atmospheric

CO₂ ¹³C/¹²C carbon isotope data by Segalstad (1992), the ~5 years obtained from CO₂ solubility data by Murray (1992), and the ~5 years derived from CO₂ chemical kinetic data by Stumm and Morgan (1970).

Revelle and Suess (1957) calculated from data for the trace atmospheric molecule ¹⁴CO₂, containing the radioactive isotope ¹⁴C, that the amount of atmospheric “CO₂ derived from industrial fuel combustion” would be only 1.2% for an atmospheric CO₂ lifetime of five years, and 1.73% for a CO₂ lifetime of seven years (Segalstad, 1998). Essenhigh (2009) reviewed measurements of ¹⁴C from 1963 through 1995 and found the RT of atmospheric ¹⁴CO₂ is ~16 (16.3) years. He also used the ¹⁴C data to determine the time value (exchange time) for variation of the concentration difference between the northern and southern hemispheres is 2.2 years for atmospheric ¹⁴CO₂. This result compares well with the observed hemispheric transport of volcanic debris leading to “the year without a summer” in 1816 in the northern hemisphere after the Tambora volcano cataclysmic eruption in Indonesia in 1815.

Sundquist (1985) compiled a large number of measured RTs of CO₂ found by different methods. The list, containing RTs for both ¹²CO₂ and ¹⁴CO₂, was expanded by Segalstad (1998), showing a total range for all reported RTs from one to 15 years, with most RT values ranging from five to 15 years. Essenhigh (2009) emphasizes this list of measured values of RT compares well with his calculated RT of five years for atmospheric bulk ¹²CO₂ and ~16 years for atmospheric trace ¹⁴CO₂. In addition, he notes the annual oscillations in the measured atmospheric CO₂ levels would be impossible without a short atmospheric residence time for the CO₂ molecules. Essenhigh further suggests the difference in atmospheric CO₂ residence times between the gaseous molecules ¹²CO₂ and ¹⁴CO₂ may be due to differences in the kinetic absorption and/or dissolution rates of the two different gas molecules.

Essenhigh also discusses alternative ways of expressing residence time, such as fill time, decay time, e-fold time, turnover time, and lifetime, and whether the Earth system carbon cycle is in dynamic equilibrium or nonequilibrium status. He concludes (like Segalstad, 1998) residence time is a robust parameter independent of the status of equilibrium, and that alternative expressions of the residence time give corresponding values.

It is important to compare Essenhigh’s results with a paper on the same topic by Solomon *et al.*

(2009), the first author of which (Susan Solomon) co-chaired the IPCC's Working Group I addressing physical climate science. The Solomon team's paper was published after Essenhigh had submitted his manuscript to *Energy & Fuels*.

Solomon *et al.* (2009) say there is an irreversible climate change in progress due to the assimilation of CO₂ in the atmosphere, caused solely by rising anthropogenic CO₂ emissions. Their vision of the future is one in which the CO₂ level flattens out asymptotically toward infinity, giving a residence time of more than 1,000 years, without offering a definition or discussion of residence time or isotopic differences: "a quasi-equilibrium amount of CO₂ is expected to be retained in the atmosphere by the end of the millennium that is surprisingly large: typically ~40% of the peak concentration enhancement over preindustrial values (~280 ppmv)." Figure 1 of that paper shows a peak level at 1,200 ppmv atmospheric CO₂ in the year 2100, leveling off to an almost steady level of ~800 ppmv in the year 3000. It is not known how the 40% estimate was derived.

Solomon *et al.* say "this can be easily understood on the basis of the observed instantaneous airborne fraction (AF^{peak}) of ~50% of anthropogenic carbon emissions retained during their build-up in the atmosphere, together with well-established ocean chemistry and physics that require ~20% of the emitted carbon to remain in the atmosphere on thousand-year timescales [quasi-equilibrium airborne fraction (AF^{equil}), determined largely by the Revelle factor governing the long-term partitioning of carbon between the ocean and atmosphere/biosphere system]."

Solomon *et al.* (2009) neglect to consider other alternatives, however, such as that offered by Segalstad (1998), who addressed the 50 percent "missing sink" error of the IPCC, showing the Revelle evasion "buffer" factor is ideologically defined from an assumed model (atmospheric anthropogenic CO₂ increase) and an assumed preindustrial value for the CO₂ level, in conflict with the chemical Henry's Law governing the fast ~1:50 equilibrium partitioning of CO₂ between gas (air) and fluid (ocean) at Earth's average surface temperature. This CO₂ partitioning factor is strongly dependent on temperature because of the temperature-dependent retrograde aqueous solubility of CO₂, which facilitates fast degassing of dissolved CO₂ from a heated fluid phase (ocean), similar to what is experienced by heating a carbonated drink.

The correct estimate of the atmospheric residence

time of CO₂ is important. The IPCC has constructed a model claiming the natural CO₂ input/output is in static balance and all CO₂ added to the atmosphere from anthropogenic carbon combustion will stay there almost indefinitely. With an anthropogenic atmospheric CO₂ residence time of 50 to 200 years (Houghton, 1990) or near-infinite (Solomon *et al.*, 2009), there remains a 50 percent error (nicknamed the "missing sink") in the IPCC's model: The measured rise in the atmospheric CO₂ level is just half of that expected from the amount of anthropogenic CO₂ supplied to the atmosphere, and carbon isotope measurements invalidate the IPCC's model (Segalstad, 1992; Segalstad, 1998).

The alternative evaluation of the CO₂ residence time—giving values of about five years for the bulk of the atmospheric CO₂ molecules, as per Essenhigh's (2009) reasoning and numerous measurements with different methods—indicates CO₂ is part of a dynamic, not static, system, where about one-fifth of the atmospheric CO₂ pool is exchanged every year between different sources and sinks due to relatively fast equilibria and temperature-dependent CO₂ partitioning governed by the chemical Henry's Law (Segalstad 1992; Segalstad, 1996; Segalstad, 1998).

Starr (1993) also found the atmospheric lifetime of CO₂ is about five years, consistent with the seasonal photosynthesis swing of atmospheric CO₂ and the bomb ¹⁴C decay history. The short residence time suggests anthropogenic emissions contribute only a fraction of the observed atmospheric rise and other sources, such as ocean and volcanic degassing of CO₂, need to be sought.

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2.2 Methane

What impact do global warming, the ongoing rise in the air’s carbon dioxide (CO₂) content, and other contemporary environmental trends have on the atmosphere’s methane (CH₄) concentration? Methane is a more powerful greenhouse gas, molecule for molecule, than is carbon dioxide. As discussed in the subsections below, there are significant forces at play that will likely produce a large negative feedback toward the future warming potential of this powerful

greenhouse gas, nearly all of which are ignored or downplayed by the IPCC.

2.2.1 Atmospheric Concentrations

Atmospheric methane’s contribution to anthropogenic climate forcing is estimated to be about half that of CO₂ when both direct and indirect components to its forcing are summed (see Figure 2.2.1.1). Nearly all models project atmospheric methane (CH₄) concentrations will increase for at least the next three decades, with many of the scenarios assuming a much larger increase throughout the twenty-first century. However, atmospheric methane concentrations currently lie far below the model projections in each of the four prior *Assessment Reports* of the IPCC (see Figure 2.2.1.2).

Shortly after release of the first IPCC *Assessment Report*, some researchers recognized the past two centuries’ dramatic increase in atmospheric methane concentrations, sparked by the Industrial Revolution, was abruptly slowing (Dlugokencky *et al.*, 1998; Francey *et al.*, 1999; Lassey *et al.*, 2000). Based on measurements from 43 globally distributed remote boundary-layer sites, Dlugokencky *et al.* (2003), for example, calculated global CH₄ concentration averages for the years 1984 to 2002. The results have been replotted in Figure 2.2.1.3, where the measurements are shown to fall into three groupings: initial and latter stages, to which have been fit linear regressions, and an intervening middle stage, to which has been fit a second-order polynomial.

Dlugokencky *et al.* noted the globally averaged atmospheric methane concentration “was constant at ~1751 ppb from 1999 through 2002,” which suggested, in their words, that “during this 4-year period the global methane budget has been at steady state.” They cautioned, “our understanding is still not sufficient to tell if the prolonged pause in CH₄ increase is temporary or permanent.”

Although initially contending in 2002 (Simpson *et al.*, 2002) it was “premature to believe that the CH₄ burden is ceasing to increase,” four years later Simpson *et al.* (2006) acknowledged the anomalous CH₄ growth spikes to which their earlier paper had referred were indeed “superimposed on an overall slowdown of the CH₄ growth rate.” The slowdown documented by Simpson *et al.* (2006) was so significant they reported “the global growth rate of atmospheric CH₄ has been near-zero for the past seven years, averaging 0.7 ± 2.6 ppbv year⁻¹.” They also state “opportunities exist for still further reduc-

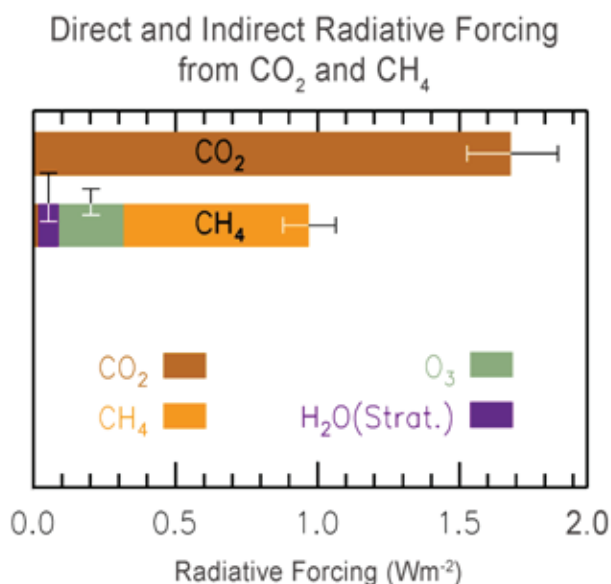


Figure 2.2.1.1. Direct and indirect radiative forcing from CO₂ and CH₄, as estimated by the IPCC. Adapted from IPCC, *Climate Change 2007: The Physical Science Basis*, p. 136, FAQ 2.1, Figure 2.

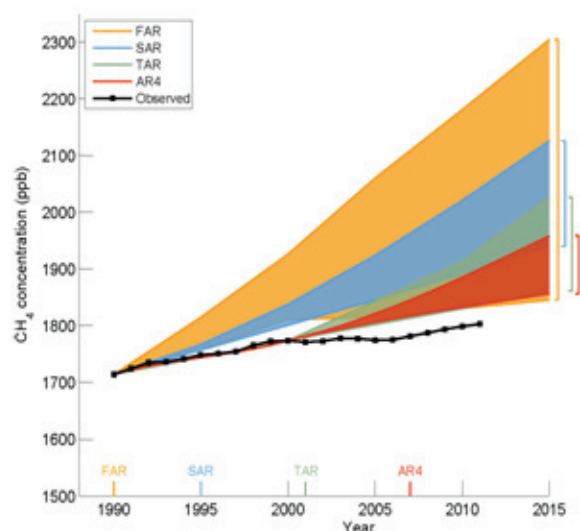


Figure 2.2.1.2. Atmospheric CH₄ projections vs observations for the first four IPCC Assessment Reports. Second Order Draft of AR5, dated October 5, 2012

tions,” noting “CH₄ levels may decrease if various CH₄ emission mitigation strategies are implemented.” They further note “the reduction of fossil fuel leakage has promise” and “because the leaking fossil fuels

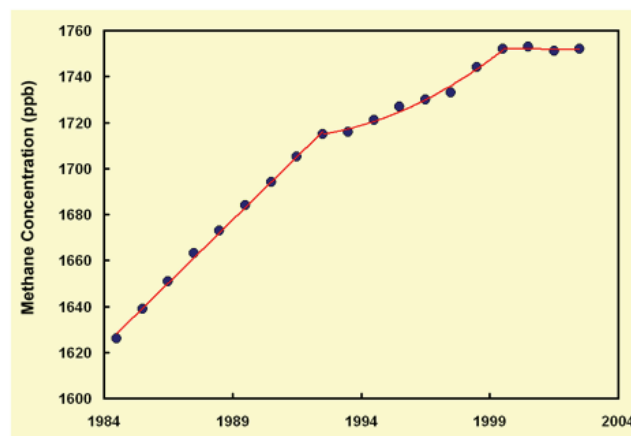


Figure 2.2.1.3. Global tropospheric methane (CH₄) concentration vs. time. Plotted from data tabulation in Dlugokencky, E.J., Houweling, S., Bruhwiler, L., Masarie, K.A., Lang, P.M., Miller, J.B., and Tans, P.P. 2003. Atmospheric methane levels off: Temporary pause or a new steady-state? *Geophysical Research Letters* **30**: 10.1029/2003GL018126.

have high value in the market, these mitigation steps can in some cases even be economically favorable.”

Simpson *et al.* (2006) point out “methane has been second only to carbon dioxide in enhanced climatic forcing from 1750 to the present.” Thus if atmospheric CH₄ levels continue to fall, rising atmospheric CO₂ levels might result in no net increase in the radiative forcing of climate. At the same time, the aerial fertilization and anti-transpirant effects of atmospheric CO₂ enrichment would grow, enhancing the efficiency of water and nutrient use by both natural and managed ecosystems. In addition, because methane is “an important source of tropospheric ozone,” as related by Simpson *et al.* (2006), the declining CH₄ concentration would alleviate much of the damage to Earth’s vegetation routinely caused by this most debilitating of air pollutants.

One year later, Khalil *et al.* (2007) combined two large atmospheric data sets to produce the unified set of data depicted in Figure 2.2.1.4, from which it is clear the rate of methane increase in the atmosphere has dropped dramatically over time. Khalil *et al.* report, “the trend has been decreasing for the last two decades until the present when it has reached near zero,” adding, “it is questionable whether human activities can cause methane concentrations to increase greatly in the future.”

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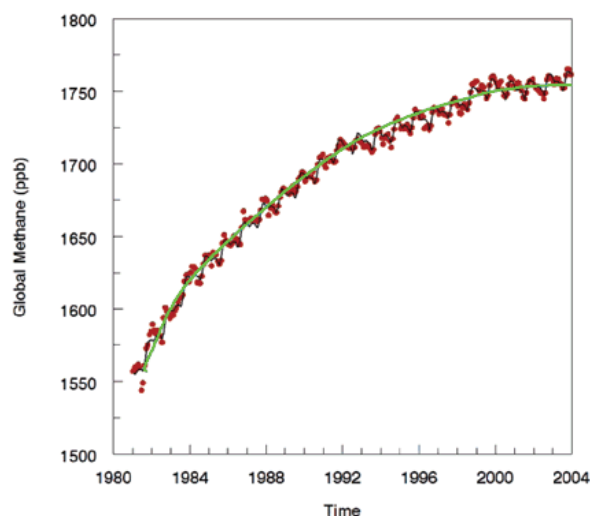


Figure 2.2.1.4. Global methane (CH_4) concentration. Adapted from Khalil, M.A.K., Butenhoff, C.L., and Rasmussen, R.A. 2007. Atmospheric methane: Trends and cycles of sources and sinks. *Environmental Science & Technology* 10.1021/es061791t.

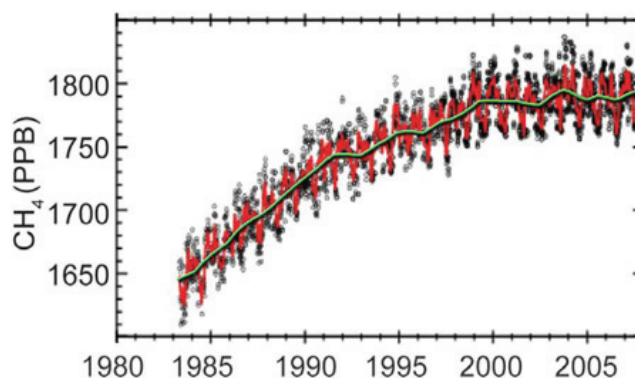


Figure 2.2.1.5. Trace gas mole fractions of methane (CH_4) as measured at Mauna Loa, Hawaii. Adapted from Schnell, R.C. and Dlugokencky, E. 2008. Methane. In: Levinson, D.H. and Lawrimore, J.H. (Eds.) *State of the Climate in 2007*. Special Supplement to the *Bulletin of the American Meteorological Society* 89: S27.

Similar findings were reported in 2008 by Schnell and Dlugokencky, who presented an update through 2007 of atmospheric methane concentrations as determined from weekly discrete samples collected on a regular basis since 1983 at the NOAA/ESRL Mauna Loa Observatory (see Figure 2.2.1.5). Schnell and Dlugokencky note “atmospheric CH_4 has remained nearly constant since the late 1990s,” the exact cause(s) of which decline “are still unclear.”

In a contemporaneous study, Rigby *et al.* (2008) analyzed CH_4 data obtained from the Advanced Global Atmospheric Gases Experiment (AGAGE)—a network of five stations located in coastal regions at latitudes from 53°N to 41°S —and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), a network of eight locations around the globe that “provides an independent and complementary data set, and a wider latitudinal site distribution.” The sixteen scientists report their methane measurements, which run from January 1997 to April 2008, “show renewed growth from the end of 2006 or beginning of 2007 until the most recent measurements,” with the record-long range of methane growth rates hovering about zero but sometimes dropping five parts per billion (ppb) per year into the negative range, while rising near the end of the record to mean positive values of eight and 12

ppb per year for the two measurement networks.

Does this recent increase provide renewed support for the IPCC’s projected increase in methane used in their model calculations of future global temperature? In a word, no—or at least not yet—for much larger increases in the methane growth rate have occurred over the past two to three decades. The most recent data from NOAA scientist Dr. Ed Dlugokencky, shown in Figure 2.2.1.6, show the global growth rate of atmospheric methane fell for nearly two decades and underwent a brief rise in 2004. That increase peaked in 2007, and since then the methane growth rate has been declining.

Only the passing of time will test the validity of atmospheric methane growth rate scenarios used by the IPCC in its projections of future climate. But if the past has taught us anything at all, it is that we do not know all we need to know about the factors that contribute to (the sources) and extract from (the sinks) methane in the atmosphere. That fact should be strikingly evident to the IPCC, whose methane projections have consistently outstretched the reality of observations in each of the prior four Assessment Reports, as illustrated earlier in Figure 2.2.1.2. The IPCC’s temperature projections, which incorporate the influence of methane, are likely overinflated as well.

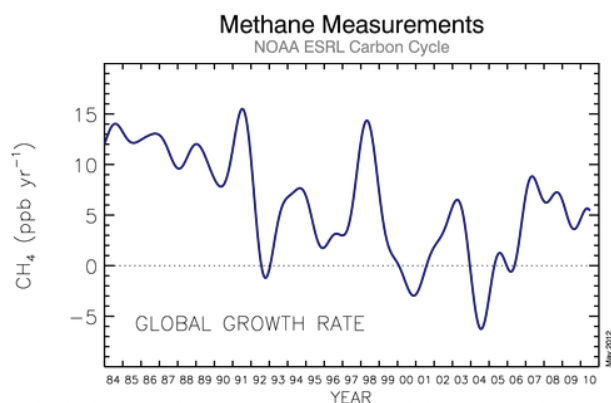


Figure 2.2.1.6. Global average growth rate of methane from the Carbon Cycle cooperative air sampling network, published by Ed Dlugokencky on the NOAA website <http://www.esrl.noaa.gov/gmd/ccgg/>.

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2.2.2 Emissions to the Atmosphere

2.2.2.1 Agriculture

What effect, if any, does the rise in atmospheric carbon dioxide levels have on atmospheric methane concentrations? As noted earlier, this question has important implications because, molecule for molecule, methane is a more powerful greenhouse gas than carbon dioxide. This question is considered here as it applies to methane emissions associated with agricultural operations.

Schrope *et al.* (1999) found atmospheric CO_2 enrichment might significantly reduce methane emissions associated with the production of rice. They studied rice growing in large vats filled with topsoil and placed in greenhouse tunnels maintained at atmospheric CO_2 concentrations of 350 and 700 ppm. Each of the tunnels was subdivided into four sections that provided temperature treatments ranging from ambient to as much as 5°C above ambient.

The researchers found doubling the air's CO_2 content enhanced rice biomass production by up to 35 percent above-ground and up to 83 percent below-ground. And in an unanticipated development, methane emissions from the rice grown at 700 ppm CO_2 were found to be 10 to 45 times lower than emissions from the plants grown at 350 ppm. As Schrope *et al.* describe it, “the results of this study did not support our hypothesis that an effect of both increased carbon dioxide and temperature would be an increase in methane emissions.” On the contrary, they note “both increased carbon dioxide and increased temperatures were observed to produce decreased methane emissions,” except for the first 2°C increase above ambient, which produced a slight increase in methane evolution from the plant-soil system.

Schrope *et al.* stated their results “unequivocally support the conclusion that, during this study,

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methane emissions from *Oryza sativa* [rice] plants grown under conditions of elevated CO₂ were dramatically reduced relative to plants grown in comparable conditions under ambient levels of CO₂.” They replicated their experiment in a second year of sampling and obtained essentially the same results.

Four years later, a study of the same phenomenon by a different set of scientists yielded a far different result under a different set of circumstances. Inubushi *et al.* (2003) grew a different cultivar of rice in 1999 and 2000 in paddy culture at Shizukuishi, Iwate, Japan in a free-air carbon dioxide enrichment (FACE) study where the air’s CO₂ concentration was increased 200 ppm above ambient. They found the extra CO₂ “significantly increased the CH₄ emissions by 38% in 1999 and 51% in 2000,” which they attributed to “accelerated CH₄ production as a result of increased root exudates and root autolysis products and to the increased plant-mediated CH₄ emission because of the higher rice tiller numbers under FACE conditions.” With such a dramatically different result from that of Schroppe *et al.*, many more studies likely will be required to clarify this relationship and determine which of these contrasting results is the more typical.

A related study was conducted by Kruger and Frenzel (2003), who note “rice paddies contribute approximately 10–13% to the global CH₄ emission (Neue, 1997; Crutzen and Lelieveld, 2001),” and “during the next 30 years rice production has to be increased by at least 60% to meet the demands of the growing human population (Cassman *et al.*, 1998).” They further note “increasing amounts of fertilizer will have to be applied to maximize yields [and] there is ongoing discussion on the possible effects of fertilization on CH₄ emissions.”

Kruger and Frenzel investigated the effects of N-fertilizer (urea) on CH₄ emission, production, and oxidation in rice culture in laboratory, microcosm, and field experiments conducted at the Italian Rice Research Institute in northern Italy. They report in some prior studies “N-fertilization stimulated CH₄ emissions (Cicerone and Shetter, 1981; Banik *et al.*, 1996; Singh *et al.*, 1996),” whereas “methanogenesis and CH₄ emission was found to be inhibited in others (Cai *et al.*, 1997; Schutz *et al.*, 1989; Lindau *et al.*, 1990).” That is similar to the polarized findings of Schroppe *et al.* and Inubushi *et al.* with respect to the effects of elevated CO₂ on methane emissions. In the mean, therefore, there may be little or no change in overall CH₄ emissions from rice fields in response to

elevated CO₂ and increased N-fertilization. With respect to their own study, for example, Kruger and Frenzel report “combining our field, microcosm and laboratory experiments we conclude that any agricultural praxis improving the N-supply to the rice plants will also be favorable for the CH₄ oxidizing bacteria,” noting “N-fertilization had only a transient influence and was counter-balanced in the field by an elevated CH₄ production.” The implication of these findings is noted in the concluding sentence of their paper: “Neither positive nor negative consequences for the overall global warming potential could be found.”

Additional understanding of CO₂-induced impacts on methane emissions from rice was gained by Cheng *et al.* (2008), who examined well-watered (flooded) and fertilized rice (*Oryza sativa* L.) plants. Plants were fumigated with air containing either 380 or 680 ppm CO₂ from the panicle formation stage at 59 days after transplanting (DAT) from seedling trays into pots within controlled-environment chambers maintained at either high (32°C) or low (22°C) night temperatures, with day temperature held constant at 32°C, until either 107 or 114 DAT. They measured the flux of methane between the pots and the atmosphere each day at 10:00 and 22:00 hours. At the conclusion of the experiment they determined the dry weight of each organ of all of the plants employed in the study.

The researchers found the extra 300 ppm of CO₂ increased CH₄ emissions by 32.2 percent in the low night temperature treatment, but by only 3.5 percent in the high night temperature treatment. They also found the elevated CO₂ increased the dry weight gained by the plants in the low night temperature treatment by 38.4 percent, but by a smaller 12.7 percent in the high night temperature treatment.

An interesting metric can be derived from these data: the ratio of the percent increase in CO₂-induced biomass production (a positive effect) to the percent increase in CO₂-induced CH₄ emissions (a negative effect) as the air’s CO₂ concentration rose from 380 to 680 ppm. This benefit/cost ratio was 1.19 in Cheng *et al.*’s low-night-temperature treatment and 3.63 in their high-night-temperature treatment. Thus, from the low-night-temperature to the high-night-temperature environment, as the air’s CO₂ concentration rose by 300 ppm, the benefit/cost ratio rose by a little more than 200 percent.

Because night temperatures rose significantly faster than day temperatures throughout most of the

world over the past several decades, this phenomenon may have had a net two-pronged *positive* effect on the biosphere, and it could have a similar positive effect in the future, increasing the aerial fertilization effect of atmospheric CO₂ enrichment at a considerably faster relative rate than the relative rate of CO₂-induced methane emissions to the atmosphere.

Introducing their study of the subject, Qaderi and Reid (2011) write the release of aerobic methane by vegetation has been indirectly confirmed by the field studies of Braga do Carmo *et al.* (2006), Crutzen *et al.* (2006), and Sanhueza and Donoso (2006), as well as by the satellite studies of Frankenberg *et al.* (2005, 2008). In addition, they note CH₄ emissions from plants can be stimulated by higher air temperatures (Vigano *et al.*, 2008; Qaderi and Reid, 2009) and water stress (Qaderi and Reid, 2009). And since “methane is the second most important long-lived greenhouse gas after carbon dioxide and is thought to be ~25 times more potent than CO₂ in its ability to act as a greenhouse gas,” as they describe it, they decided to see what effect the ongoing rise in the air’s CO₂ content might have on this phenomenon.

Qaderi and Reid “examined the combined effects of temperature, carbon dioxide and watering regime on CH₄ emissions from six commonly cultivated crop species: faba bean, sunflower, pea, canola, barley and wheat” in an experiment where “plants were grown from seeds in controlled-environment growth chambers under two temperature regimes (24°C day/20°C night and 30°C day/26°C night), two CO₂ concentrations (380 and 760 ppm) and two watering regimes (well watered and water stressed),” where the “plants were first grown under 24/20°C for one week from sowing, and then placed under experimental conditions for a further week,” after which “plant growth, gas exchange and CH₄ emission rates were determined.”

The researchers found “no detectable CH₄ from [a] control treatment (without plant tissue), indicating that CH₄ from the experimental treatments was emitted only from plant tissues.” Second, they found the plants grown under higher temperature and water stress emitted more CH₄ than those grown under lower temperature and no water stress. And third, they found “elevated CO₂ had the opposite effect,” “partially revers[ing]” the effects of the other two factors.

Qaderi and Reid comment, “although rising atmospheric CO₂ reduces plant CH₄ emissions, it may not fully reverse the effects of temperature and drought,” which they assumed would increase in

tandem with the ongoing rise in the air’s CO₂ content.

Another agricultural source of methane is the fermentation of feed in the rumen of cattle and sheep. Boadi *et al.* (2004) reviewed methods for reducing CH₄ emissions from dairy cows. At the time of their review, existing mitigation strategies for reducing emissions from dairy cows included the addition of ionophores and fats to their food and the use of high-quality forages and grains in their diet, while newer mitigation strategies included “the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, [and] plant extracts (e.g., essential oils) to the diet, as well as immunization, and genetic selection of cows.” The researchers provide a table of 20 such strategies, where the average maximum potential CH₄ reduction that may result from the implementation of each strategy is 30 percent or more.

Fievez *et al.* (2003) studied the effects of various types and levels of fish-oil feed additives on this process by means of both *in vitro* and *in vivo* experiments with sheep, observing a maximal 80 percent decline in the ruminants’ production of methane when using fish-oil additives containing n-3-eicosapentanoic acid. The presence of condensed tannins found in certain pasture plants also can reduce methane emissions from sheep and cattle, which account for approximately 90 percent of New Zealand’s methane emissions. Enriching the air with CO₂ can increase the tannin concentrations of many forage plants.

It is thus possible increasing condensed tannin concentrations in pasture crops by genetic engineering and allowing the air’s CO₂ content to continue to rise could result in significant decreases in methane emissions from cattle and sheep. The outlook is also good for accomplishing this feat by including fish-oil feed additives in their diets. In addition, it is possible elevated CO₂ concentrations may lead directly to reduced methane emissions from rice culture, although more work must be done to test this hypothesis. Nevertheless, the balance of evidence suggests we can be cautiously optimistic about our agricultural intervention capabilities and their capacity to help stem the tide of Earth’s historically rising atmospheric methane concentration.

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2.2.2.2 Natural Vegetation

Continuing our investigation of the effect of rising temperature, rising atmospheric carbon dioxide (CO₂)

concentrations, and other environmental trends on the atmosphere's methane (CH₄) concentration, in this section we consider methane emissions associated with natural vegetation.

Frolking and Roulet (2007) point out “throughout the Holocene, northern peatlands have both accumulated carbon and emitted methane,” and “their impact on climate radiative forcing has been the net of cooling (persistent CO₂ uptake) and warming (persistent CH₄ emission).” They developed Holocene peatland carbon flux trajectories based on estimates of contemporary CH₄ flux, total accumulated peat C, and peatland initiation dates, which they used as inputs to a simple atmospheric perturbation model to calculate the net radiative impetus for surface air temperature change.

Frolking and Roulet note early in the Holocene the capture of CO₂ and emission of CH₄ by Earth's northern peatlands was likely to have produced a net warming impetus of up to +0.1 W m⁻². Over the following 8,000 to 11,000 years, however, they say Earth's peatlands have been doing the opposite, such that the current radiative forcing due to these atmospheric CO₂ and CH₄ perturbations represents a net cooling force on the order of -0.22 to -0.56 W m⁻². The impetus for global cooling due to carbon sequestration by Earth's peatlands historically has been—and currently is—significantly greater than the global warming potential produced by peatlands' emissions of methane.

Toet *et al.* (2001) point out, “only three previous published studies have assessed the impacts of O₃ on CH₄ and CO₂ fluxes in peatlands.” Niemi *et al.* (2002), as they describe it, “reported that CH₄ emissions more than doubled when peatland microcosms were exposed to 100 ppb O₃ over 4–7 weeks during summer in controlled-environment chambers.” In contrast, they note, “Rinnan *et al.* (2003) reported no significant effect on CH₄ emissions of a 7-week exposure of peat microcosms to 100 or 200 ppb O₃.” Finally, they note “Morsky *et al.* (2008) reported that open-field exposure of boreal peatland microcosms in central Finland to a doubling of ambient O₃ concentrations caused a decrease in CH₄ emission at the end of the first growing season,” but they note the decrease “was lost in the three subsequent growing seasons.” Prior work on the subject thus has not provided a definitive answer to the core question of whether rising O₃ concentrations have a significant effect on methane emissions from peatlands.

In a study more reflective of reality in terms of

scale, Toet *et al.* moved up in size from microcosms to mesocosms, collected from a lowland raised bog on the northern shore of Morecambe Bay, Cumbria, UK (54°13'N, 3°1'W) and subsequently placed into open-top chambers situated on a level gravel base at Newcastle University's field station (54°59'N, 1°48'W). For the next two years they observed what happened in four ambient and four O₃-enriched chambers, the latter of which had their atmospheric O₃ concentrations raised by 50 ppb for eight hours of each day during the summer period (April-early October) and by 10 ppb for eight hours of each day throughout the winter.

The researchers found “methane emissions were significantly reduced, by about 25%, by elevated ozone during midsummer periods of both years,” but “no significant effect of ozone was found during the winter periods.” After a lengthy discussion of their findings and those of other researchers they cite, Toet *et al.* conclude, in the final sentence of their paper, “increased O₃ could be a significant brake on the increased flux of CH₄ that is expected as these northern peatlands warm.”

Davidson *et al.* (2004) report the climate of the Amazon Basin may become gradually drier due to the intensification of a number of different phenomena, including (1) less recirculation of water between the increasingly deforested region and the atmosphere, (2) more rainfall inhibition by smoke caused by increased biomass burning, and (3) a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the eastern Amazon Basin (Nepstad *et al.*, 1999; see Timmermann *et al.*, 1999 as well). They devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of two important greenhouse gases: nitrous oxide (N₂O) and methane (CH₄).

In the Tapajos National Forest near Santarem, Brazil, the researchers modified a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the amount of rain that reached the forest floor (throughfall) while maintaining an otherwise-similar one-hectare plot of land as a control for comparison. Prior to making this modification, they measured the gas exchange characteristics of the two plots for a period of 18 months. After initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This protocol revealed, in their words, that the “drier soil conditions caused by throughfall exclusion inhibited

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N₂O and CH₄ production and promoted CH₄ consumption.” They state “the exclusion manipulation lowered annual N₂O emissions by >40% and increased rates of consumption of atmospheric CH₄ by a factor of >4,” which they attribute to the “direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy.”

If global warming did indeed increase the frequency and/or intensity of El Niño events—which real-world data suggest is highly debatable (see Chapter 4)—the work of Davidson *et al.* (2004) suggests the anticipated drying of the Amazon Basin would initiate a strong negative feedback to warming via drying-induced reductions in the evolution of N₂O and CH₄ from its soils and a drying-induced increase in the consumption of CH₄ by its soils. Although Davidson *et al.* envisaged a more extreme second phase response, “in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots” (a response that would be expected to increase N₂O and CH₄ emissions), it should be noted the projected rise in the air’s CO₂ content likely would prohibit such extreme events from occurring, in light of the tendency for elevated levels of atmospheric CO₂ to increase the water use efficiency of plants, which would enable the Amazon Basin’s vegetation to continue to flourish under significantly drier conditions than those of the present.

Strack *et al.* (2004) also note climate models predict increases in evapotranspiration that could lead to drying in a warming world and a subsequent lowering of water tables in high northern latitudes. This prediction stresses the importance of determining how lowered water tables will affect peatland emissions of CH₄. In a theoretical study of the subject, Roulet *et al.* (1992) calculated that for a decline of 14 cm in the water tables of northern Canadian peatlands, due to climate-model-derived increases in temperature (3°C) and precipitation (1mm/day) predicted for a doubling of the air’s CO₂ content, CH₄ emissions would decline by 74 to 81 percent. In an attempt to obtain some experimental data on the subject, over the period 2001–2003 Strack *et al.* measured CH₄ fluxes to the atmosphere at different locations that varied in depth-to-water table within natural portions of a poor fen in central Quebec, Canada as well as within control portions of the fen that had been drained eight years earlier.

The Canadian scientists report, “methane

emissions and storage were lower in the drained fen.” The greatest reductions (up to 97 percent) were measured at the higher locations, whereas at the lower locations there was little change in CH₄ flux. Averaging the results over all locations, the researchers determined the “growing season CH₄ emissions at the drained site were 55% lower than the control site,” indicating the biosphere appears to be able to resist warming influences.

In one final study of anaerobic conditions, Garnet *et al.* (2005) grew seedlings of three emergent aquatic macrophytes (*Orontium aquaticum* L., *Peltandra virginica* L., and *Juncus effusus* L.) and one coniferous tree (*Taxodium distichum* L.), all of which are native to eastern North America, in a five-to-one mixture of well-fertilized mineral soil and peat moss in pots submerged in water in tubs located within controlled environment chambers for a period of eight weeks. Concomitantly, they measured the amount of CH₄ emitted by the plant foliage, along with net CO₂ assimilation rate and stomatal conductance, which were made to vary by changing the CO₂ concentration of the air surrounding the plants and the density of the photosynthetic photon flux impinging on them.

The researchers found methane emissions from the four wetland species increased linearly with increases in both stomatal conductance and net CO₂ assimilation rate, but changes in stomatal conductance affected foliage methane flux “three times more than equivalent changes in net CO₂ assimilation,” making stomatal conductance the more significant of the two CH₄ emission-controllers. They note evidence of stomatal control of CH₄ emission also has been reported for *Typha latifolia* (Knapp and Yavitt, 1995) and *Carex* (Morrissey *et al.*, 1993), two other wetland plants. Since atmospheric CO₂ enrichment leads to approximately equivalent but oppositely directed changes in foliar net CO₂ assimilation (which is increased) and stomatal conductance (which is reduced) in most herbaceous plants (the type that comprise most wetlands), it can be appreciated that the ongoing rise in the air’s CO₂ content should be acting to reduce methane emissions from Earth’s wetland vegetation.

Shifting to studies examining aerobic conditions, Dueck *et al.* (2007) point out recent findings suggest terrestrial plants may “emit methane under aerobic conditions by an as yet unknown physiological process (Keppler *et al.*, 2006), and in this way may substantially contribute to the annual global methane budget (Bousquet *et al.*, 2006),” resulting in

“estimated values for methane emission by terrestrial plants varying between 10 and 260 Tg yr⁻¹ (Houweling *et al.*, 2006; Keppler *et al.*, 2006; Kirschbaum *et al.*, 2006).” The 15 Dutch researchers conducted two experiments involving six plant species—*Ocimum basilicum* L. (basil), *Triticum aestivum* L. (wheat), *Zea mays* L. (maize), *Salvia officinalis* L. (sage), *Lycopersicon esculentum* Miller (tomato), and *Oenothera biennis* L. (common evening primrose)—the first three of which also were used by Keppler *et al.* (2006).

The experiments were performed in “a unique hermetically sealed plant growth chamber with a volume of 3500 liters, specifically designed for atmospheric isotope labeling,” where “plants were grown hydroponically to exclude any methane production derived from anaerobic soil pockets.” Dueck *et al.* reported there was no evidence for substantial aerobic methane emission by the terrestrial plants they studied, stating, “maximally,” it was only “0.3% of the previously published studies.” They indicate methane concentrations in continuous-flow gas cuvettes with plants “were not significantly higher than those of control cuvettes without plants,” stating for both short and long terms, they “did not find any evidence of a substantial emission of methane.”

Keppler *et al.*’s findings have been further challenged by other researchers. Beerling *et al.* (2008), for example, raised the C₄ plant *Zea mays* and the C₃ plant *Nicotiana tabacum* from seed for six weeks at an ambient CO₂ concentration of 400 ppm and an ambient methane concentration of 1,800 ppb, after which their leaves were studied in “a custom-built flowthrough cuvette with a sufficiently large area to allow the detection of methane emissions” via “a process gas chromatograph linked to a high-precision, high-accuracy flame ionization detector” in a controlled-environment room. The team of five U.K. researchers report “well-illuminated actively photosynthesizing *Z. mays* leaves did not, in our experimental system, emit substantial quantities of methane during repeated three-hour high irradiance episodes,” and “neither did we detect methane emissions from actively respiring leaves during repeated three-hour dark periods.” They additionally state “measurements with leaves of the C₃ species *N. tabacum* also failed to detect substantial aerobic methane emissions in the light when photosynthesizing with regular stomatal conductances, and in the dark when respiring.”

Nisbet *et al.* (2009) “conducted further experiments on plants grown in controlled

conditions” and “re-analyzed the previously published data” on the topic. The 14 researchers (13 from the U.K. and one from Sweden) demonstrated “plants do not contain a biochemical mechanism for methanogenesis” and “cannot produce methane as an end-product or by-product of their metabolism.” The researchers determined “when plants transpire, any methane that is already dissolved in the water derived from the soil will be released into the atmosphere” and “under high stress conditions, such as high UV radiation, methane is released as part of the cellular breakdown process.” In light of such findings, plus “a new analysis of global methane levels from satellite retrievals,” Nisbet *et al.* conclude “plants are not a major source of the global methane production.” They do, however, acknowledge “the role of plants in moving methane about”—that is, their importance in the global cycling of methane, but not its production.

Wang *et al.* (2009) conclude after their review of the scientific literature that “aerobic CH₄ [methane] emissions from plants may be affected by O₂ stress or any other stress leading to ROS [reactive oxygen species] production,” leading the team of researchers to examine whether physical injury also would affect CH₄ emissions from plants. Their work revealed “physical injury (cutting) stimulated CH₄ emissions from fresh twigs of *Artemisia* species under aerobic conditions” and “more cutting resulted in more CH₄ emissions,” as did hypoxia in both cut and uncut *Artemisia frigida* twigs.

In discussing their findings and those of previous studies that suggest, in their words, “that a variety of environmental stresses stimulate CH₄ emission from a wide variety of plant species,” Wang *et al.* conclude “global change processes, including climate change, depletion of stratospheric ozone, increasing ground-level ozone, spread of plant pests, and land-use changes, could cause more stress in plants on a global scale, potentially stimulating more CH₄ emission globally,” while further concluding “the role of stress in plant CH₄ production in the global CH₄ cycle could be important in a changing world.”

While many factors “could” be important in stimulating methane emissions, the ongoing rise in the air’s CO₂ content is countering stress-induced CH₄ emissions from plants. Although environmental stresses of all types generate highly reactive oxygenated compounds that damage plants, atmospheric CO₂ enrichment typically boosts the production of antioxidant enzymes that scavenge and detoxify those oxygenated compounds. The rise in the air’s CO₂ content should have been alleviating the

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level of stress experienced by Earth's plants, and this phenomenon should have been reducing the rate at which the planet's vegetation releases CH₄ to the atmosphere. Perhaps that is why the rate-of-rise of the atmosphere's methane concentration has changed little in recent decades.

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2.2.3 Extraction from the Atmosphere

Methane is an important greenhouse gas, contributing roughly 20 percent of total non-H₂O radiative forcing (Menyailo and Hungate, 2003). Its atmospheric concentration is determined by the difference between how much CH₄ goes into the air (emissions) and how much comes out of it (extractions) over any particular time period. In this section we examine factors that act to extract methane from the atmosphere.

According to Prinn *et al.* (1992), one of the major means by which methane is removed from the atmosphere is via oxidation by methanotrophic bacteria in the aerobic zones of soils; the magnitude of this phenomenon is believed to be equivalent to the annual input of methane to the atmosphere (Watson *et al.*, 1992). This soil sink for methane appears to be ubiquitous, as methane uptake has been observed in soils of tundra (Whalen and Reeburgh, 1990), boreal forests (Whalen *et al.*, 1992), temperate forests (Steudler *et al.*, 1989; Yavitt *et al.*, 1990), grasslands (Mosier *et al.*, 1997), arable lands (Jensen and Olsen, 1998), tropical forests (Keller, 1986; Singh *et al.*, 1997), and deserts (Striegl *et al.*, 1992). Forest soils—especially boreal and temperate forest upland soils (Whalen and Reeburgh, 1996)—appear to be the most efficient (Le Mer and Roger, 2001).

Tamai *et al.* (2003) studied methane uptake rates by the soils of three Japanese cypress plantations composed of 30- to 40-year-old trees. Through all seasons of the year, they found methane was absorbed by the soils of all three sites, being positively correlated with temperature, as has been observed in several other studies (Peterjohn *et al.*, 1994; Dobbie and Smith, 1996; Prieme and Christensen, 1997; Saari *et al.*, 1998). Methane absorption was even more strongly positively correlated with the C/N ratio of the cypress plantations' soil organic matter.

Based on these results, it can be surmised that CO₂-induced global warming is capable of producing two biologically mediated negative feedbacks to counter the increase in temperature: a warming-induced increase in methane uptake from the atmosphere that is experienced by essentially all soils,

and an increase in soil methane uptake from the atmosphere produced by the increase in plant-litter C/N ratio that typically results from atmospheric CO₂ enrichment.

Menyailo and Hungate (2003) assessed the influence of six boreal forest species—spruce, birch, Scots pine, aspen, larch, and Arolla pine—on soil CH₄ consumption in a Siberian artificial afforestation experiment, in which the six common boreal tree species had been grown under common garden conditions for the past 30 years under the watchful eye of the staff of the Laboratory of Soil Science of the Institute of Forest, Siberian Branch of the Russian Academy of Sciences (Menyailo *et al.*, 2002). The authors determined “soils under hardwood species (aspen and birch) consumed CH₄ at higher rates than soils under coniferous species and grassland.” Under low soil moisture conditions, for example, the soils under the two hardwood species consumed 35 percent more CH₄ than the soils under the four conifers, while under high soil moisture conditions they consumed 65 percent more. As for the implications of these findings, Pastor and Post (1988) suggested, in the words of Menyailo and Hungate, that “changes in temperature and precipitation resulting from increasing atmospheric CO₂ concentrations will cause a northward migration of the hardwood-conifer forest border in North America.” If such a shifting of species occurs, it likely will lead to an increase in methane consumption by soils and a reduction in methane-induced global warming potential—a biologically mediated negative feedback factor that is not reflected in models of global climate change.

More recently, Livesley *et al.* (2009) wrote, “soils provide the largest terrestrial carbon store, the largest atmospheric CO₂ source, the largest terrestrial N₂O [nitrous oxide] source and the largest terrestrial CH₄ sink, as mediated through root and soil microbial processes” and “a change in land use or management can alter these soil processes such that net greenhouse gas exchange may increase or decrease.” As Mutuo *et al.* (2005) have noted, “intensified agricultural practices lead to a reduction in ecosystem carbon stocks, mainly due to removal of aboveground biomass as harvest and loss of carbon as CO₂ through burning and/or decomposition,” such as occurs in response to tillage operations. Mutuo *et al.* further report upland forests typically consume methane, and “conversion of tropical forest soils to agriculture in general has been shown to reduce the sink strength for methane (Keller *et al.*, 1990; Keller and Reiners, 1994; Steudler *et al.*, 1996; Verchot *et al.*, 2000)” by

50 percent or more.

Seeking to learn more about how greenhouse gas emission and absorption differ between forests and pastures, Livesley *et al.* (2009) “measured soil-atmosphere exchange of CO₂, N₂O and CH₄ in four adjacent land-use systems (native eucalypt woodland, clover-grass pasture, *Pinus radiata* and *Eucalyptus globulus* plantation) for short, but continuous, periods between October 2005 and June 2006 using an automated trace gas measurement system near Albany in southwest Western Australia.” The six scientists discovered soil N₂O emissions were more than an order of magnitude greater in the pasture than in the natural and managed forests, while soil CH₄ uptake was greatest in the native woodland, even though the measured rates of uptake there were, as they describe it, “still small when compared with many other studies on native forest soils worldwide.” They determined the pasture soil had the least soil CH₄ uptake (a mean of 17 percent of that in the native woodland) and that it was an occasional CH₄ source, “possibly related to its greater soil water status, greater soil nitrogen status and possible differences in soil microbial community structure.” In between these two extremes, they found “afforestation with pines or eucalypts increased CH₄ uptake to 32% and 43% of that in the native woodland, respectively.” With respect to CO₂, they noted “it is widely accepted that afforestation leads to an increase in carbon sequestration through tree biomass growth.”

Livesley *et al.* reported their study confirmed “there is a triple greenhouse-gas benefit from afforestation of pasture systems,” noting in addition to carbon sequestration via tree biomass, “there is a decrease in N₂O emissions because of lower nitrogen inputs and a tighter nutrient cycling, and an increase in CH₄ uptake by forest soils.”

Guckland *et al.* (2009) conducted a two-year study of a deciduous mixed forest in the Hainich National Park, Thuringia, Germany, where they established 18 sub-plots spread throughout three types of forest and, using dark closed chambers from September 2005 to September 2007, they measured net fluxes of CH₄ every two weeks. Stand A, as they describe it, “was a single-species stand covered with European beech as the predominant tree species,” while stand B “was a three-species stand with beech, ash and lime as predominant species, and stand C was covered with beech, ash, lime, hornbeam and maple as predominant species.”

Guckland *et al.* report “the variation of CH₄

uptake over time could be explained to a large extent by changes in soil moisture in the upper five centimeters of the mineral soil,” such that “the CH₄ uptake during the main growing period (May–September) increased considerably with decreasing precipitation rate.” This finding, they write, is “in accordance with the general observation that soil moisture is the primary environmental control on CH₄ uptake in soils because it regulates methane flux into the soil through diffusion (Smith *et al.*, 2000; Butterbach-Bahl and Papen, 2002; Borken *et al.*, 2006).” They also report the methane flux response to soil moisture content was linear, as has been found to be the case in other studies (Dobbie and Smith, 1996; Bradford *et al.*, 2001; Price *et al.*, 2003). In addition, they observed “low CH₄ uptake activity during winter was further reduced by periods with soil frost and snow cover.” Such findings, in the words of the three researchers, “suggest that climate change [in this case, global warming] will result in increasing CH₄ uptake rates in this region because of the trend to drier summers and warmer winters.”

Carter *et al.* (2011) introduce their study of the subject by stating, “in temperate regions, climate change is predicted to increase annual mean temperature and intensify the duration and frequency of summer droughts, which together with elevated atmospheric carbon dioxide concentrations, may affect the exchange of nitrous oxide and methane between terrestrial ecosystems and the atmosphere.” Working in a dry temperate heathland with a nutrient-poor sandy soil located about 50 km northwest of Copenhagen, Denmark—the vegetation of which was dominated by Scotch Heather (*Calluna vulgaris*), Wavy Hairgrass (*Deschampsia flexuosa*), and various mosses—Carter *et al.* investigated “the effects of future climatic and atmospheric conditions on the biosphere-atmosphere exchange of N₂O and CH₄.”

The eight Danish researchers report warming by itself increased CH₄ uptake by about 20 percent, whereas “elevated concentrations of atmospheric CO₂ had no overall effect on the CH₄ flux, but reduced the CH₄ uptake during one measuring campaign in the winter season.” They add, “in combination, the stimulating effect of warming and the episodic reducing effect of CO₂ on the CH₄ uptake resulted in a modest, but insignificant, increase in the CH₄ uptake when comparing the multifactor treatment including elevated CO₂, warming and summer drought with the ambient treatment.” Carter *et al.* conclude their study “highlights the importance of evaluating climate

change parameters in multifactor treatments as the response of CH₄ and N₂O flux rates to different two- and three-factor combinations may not be predicted from the responses to the individual treatments.” They further state “overall, our study suggests that in the future, CH₄ uptake may increase slightly, while N₂O emission will remain unchanged in temperate ecosystems on well-aerated soils.”

Zheng *et al.* (2012) reiterate that “methane is the second most important greenhouse gas contributing roughly 20% to observed global warming (IPCC, 2007),” while adding “oxidation of CH₄ in soil by methane-oxidizing bacteria (methanotrophs) currently removes 30 Tg annually from the atmosphere, which equals 5.4% of the global CH₄ sink (IPCC, 2007).” They note CH₄-eating bacteria “play a critical role in the mitigation of global warming.” Exploring this potential role further, Zheng *et al.* studied the effects of a 1.2°C higher daylight temperature together with a 1.7°C higher nighttime temperature, with and without continuous concomitant grazing by adult Tibetan sheep, on methanotrophic abundance, community composition, and activity. The work was conducted at the Haibei Alpine Meadow Ecosystem Research Station of the Chinese Academy of Sciences in Qinghai Province in the northeastern corner of the Tibetan Plateau, while utilizing the infrared heating system and free-air temperature enhancement protocol developed by Kimball *et al.* (2008).

In the non-grazed treatments, Zheng *et al.* (2012) found the experimental warming increased methanotrophic abundance by approximately 93 percent, while in the grazed treatments, warming boosted methanotrophic abundance by more than twice that amount (183 percent) (see Figure 2.2.3.1).

Zheng *et al.* conclude the Tibetan Plateau “may remove more CH₄ [from the atmosphere] under future climate conditions.” By inference, that will likely be the case almost everywhere, as they note “methanotrophs are widely distributed in various environments (e.g., McDonald *et al.*, 2008; Op den Camp *et al.*, 2009; Semrau *et al.*, 2010), such as in paddy soils (Bodelier *et al.*, 2000; Zheng *et al.*, 2008), forest soils (Mohanty *et al.*, 2007; Kolb, 2009), landfill soils (Chen *et al.*, 2007; Einola *et al.*, 2007; Semrau, 2011), grassland soils (Zhou *et al.*, 2008; Abell *et al.*, 2009), oil field soil (Zhang *et al.*, 2010), and extreme thermoacidophilic environments (Dunfield *et al.*, 2007; Pol *et al.*, 2007; Islam *et al.*, 2008).” This terrestrial effect of global warming constitutes a significant biologically induced negative feedback, independent of the additional feedbacks

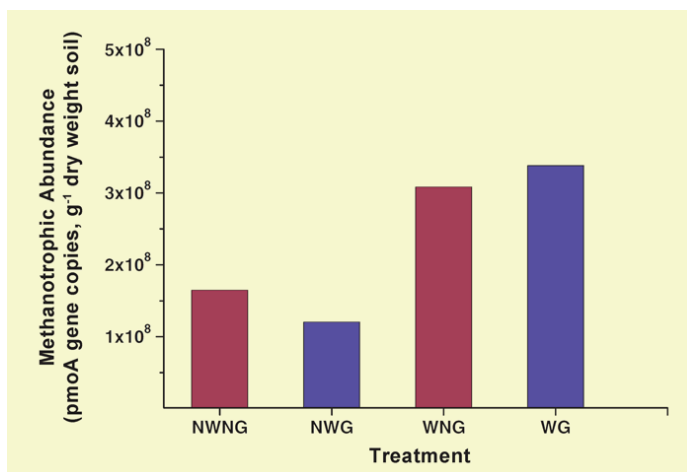


Figure 2.2.3.1. Methanotrophic abundance, expressed as the number of pmoA gene copies of methanotrophs in the soils of the four different treatments (NWNG no warming with no grazing, NWG no warming with grazing, WNG warming with no grazing, WG warming with grazing). Adapted from Zheng, Y., Yang, W., Sun, X., Wang, S.-P., Rui, Y.-C., Luo, C.-Y., and Guo, L.-D. 2012. Methanotrophic community structure and activity under warming and grazing of alpine meadow on the Tibetan Plateau. *Applied Microbiology and Biotechnology* **93**: 2193–2203.

described above that are brought about by mere increases in the air’s CO₂ concentration.

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2.3 Nitrous Oxide

Nitrous oxide (N_2O) is an influential greenhouse gas, with a global warming potential approximately 300 times that of CO_2 on a per-molecule basis (IPCC, 2001). According to Cantarel *et al.* (2011), nitrous oxide “has shown linear increases of 0.2–0.3% per year over the last few decades, largely as a result of changes in agricultural practices and direct emissions from agricultural soils (IPCC, 2007).”

Consequently, understanding the factors that control the concentration of N_2O in the atmosphere and how the sources and sinks of N_2O vary with changes in climate and other factors is an important concern among the scientific community. This section reviews research that has been conducted on this topic, beginning with a discussion of studies examining how increases in atmospheric CO_2 might modify the release of N_2O into the atmosphere.

One of the main sources of nitrous oxide is agriculture, which accounts for almost half of N_2O emissions in some countries (Pipatti, 1997). And with N_2O originating from microbial N cycling in soil—mostly from aerobic nitrification or from anaerobic denitrification (Firestone and Davidson, 1989)—there is a concern that CO_2 -induced increases in carbon input to soil, together with increasing N input from other sources, will increase substrate availability for denitrifying bacteria and may result in higher N_2O emissions from agricultural soils as the air’s CO_2 content continues to rise.

In a study designed to investigate this possibility, Kettunen *et al.* (2007a) grew mixed stands of timothy (*Phleum pratense*) and red clover (*Trifolium pratense*) in sandy-loam-filled mesocosms at low and moderate soil nitrogen levels within greenhouses maintained at either 360 or 720 ppm CO_2 , while measuring harvestable biomass production and N_2O

evolution from the mesocosm soils over the course of three crop cuttings. This work revealed the total harvestable biomass production of *P. pratense* was enhanced by the experimental doubling of the air’s CO_2 concentration by 21 percent and 26 percent, respectively, in the low and moderate soil N treatments, while corresponding biomass enhancements for *T. pratense* were 22 percent and 18 percent. In addition, the researchers found after emergence of the mixed stand and during vegetative growth before the first harvest and N fertilization, N_2O fluxes were higher under ambient CO_2 in both the low and moderate soil N treatments. It was not until the water table had been raised and extra fertilization given after the first harvest that the elevated CO_2 seemed to increase N_2O fluxes.

The four Finnish researchers conclude the mixed stand of *P. pratense* and *T. pratense* was “able to utilize the increased supply of atmospheric CO_2 for enhanced biomass production without a simultaneous increase in the N_2O fluxes,” thereby raising “the possibility of maintaining N_2O emissions at their current level, while still enhancing the yield production [via the aerial fertilization effect of elevated CO_2] even under low N fertilizer additions.”

Kettunen *et al.* (2007b) also grew timothy (*Phleum pratense*) in monoculture within sandy-soil-filled mesocosms located within greenhouses maintained at atmospheric CO_2 concentrations of either 360 or 720 ppm for a period of 3.5 months at moderate (standard), low (half-standard), and high (1.5 times standard) soil N supply, while they measured the evolution of N_2O from the mesocosms, vegetative net CO_2 exchange, and final above- and below-ground biomass production over the course of three harvests. The elevated CO_2 concentration increased the net CO_2 exchange of the ecosystems (which phenomenon was primarily driven by CO_2 -induced increases in photosynthesis) by about 30 percent, 46 percent, and 34 percent at the low, moderate, and high soil N levels, respectively. The elevated CO_2 increased the above-ground biomass of the crop by about 8 percent, 14 percent, and 8 percent at the low, moderate, and high soil N levels, and its below-ground biomass by 28 percent, 27 percent, and 41 percent at the same respective soil N levels. Kettunen *et al.* report once again, “an explicit increase in N_2O fluxes due to the elevated atmospheric CO_2 concentration was not found.”

While working at the Nevada Desert FACE facility northwest of Las Vegas, Nevada (USA),

McCalley *et al.* (2011) measured soil fluxes of reactive N gases (NO , NO_y , NH_3) and N_2O in plots receiving long-term fumigation with ambient (380 ppm) and elevated (550 ppm) CO_2 . These treatments were begun in April 1997; reactive N gas flux measurements were made under these conditions several years later in April 2005, July 2005, July 2006, January 2007, and March 2007, as well as after the termination of CO_2 fumigation in July 2007, October 2007, January 2008, and April 2008.

The five researchers report “long-term exposure to elevated CO_2 decreased reactive N gas emissions from Mojave Desert soils” primarily “in islands of fertility created by the dominant shrub *Larrea tridentata*,” especially “in the spring and fall when recent precipitation, either natural or artificial, created soil conditions that are optimal for biological activity.” Emissions of N_2O , on the other hand, were “a very small component” of gaseous N loss and were “largely insensitive to elevated CO_2 .” In addition, the five researchers state the greater-than-60 percent reductions in reactive N gas fluxes during periods of peak N demand imply elevated CO_2 is “increasing the retention of biologically available N during critical growth periods,” a major benefit for desert ecosystems.

As reported earlier in our discussion of methane extraction from the atmosphere, Livesley *et al.* (2009) point out “soils provide the largest terrestrial carbon store, the largest atmospheric CO_2 source, the largest terrestrial N_2O source and the largest terrestrial CH_4 sink, as mediated through root and soil microbial process” and “a change in land use or management can alter these soil processes such that net greenhouse gas exchange may increase or decrease.” Seeking to determine how the emission and absorption of these three greenhouse gases differ between forests and pastures, they “measured soil-atmosphere exchange of CO_2 , N_2O and CH_4 in four adjacent land-use systems (native eucalypt woodland, clover-grass pasture, *Pinus radiata* and *Eucalyptus globulus* plantation) for short, but continuous, periods between October 2005 and June 2006 using an automated trace gas measurement system near Albany in southwest Western Australia.”

With respect to nitrous oxide, the six scientists discovered soil N_2O emissions were more than an order of magnitude greater in the pasture than in the natural and managed forests. Given the authors’ findings with respect to CO_2 and CH_4 , they conclude “there is a triple greenhouse-gas benefit from afforestation of pasture systems,” where in addition to

carbon sequestration via tree biomass, “there is a decrease in N_2O emissions because of lower nitrogen inputs and a tighter nutrient cycling, and an increase in CH_4 uptake by forest soils.”

In a different type of study, driven by the possibility that the climate of the Amazon Basin may gradually become drier due to a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the region, Davidson *et al.* (2004) devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of both N_2O and methane (CH_4).

As we reported earlier in our discussion of this study with respect to methane, the researchers modified a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the amount of rain that reached the forest floor (throughfall), while maintaining an otherwise similar one-hectare plot of land as a control for comparison. Prior to making this modification, the three researchers measured the gas exchange characteristics of the two plots for a period of 18 months, and after initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This work revealed the “drier soil conditions caused by throughfall exclusion inhibited N_2O and CH_4 production and promoted CH_4 consumption.” They note “the exclusion manipulation lowered annual N_2O emissions by >40 percent and increased rates of consumption of atmospheric CH_4 by a factor of >4,” which they attributed to the “direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy.”

Other researchers also have examined the relationship between nitrous oxide emissions and soil water status. Goldberg and Gebauer (2009), for example, investigated the influence of drying and rewetting events on N_2O emissions from the soil of a mature Norway spruce forest in Northeast Bavaria, Germany. They point out “the only sink for N_2O considered in global models is the destruction of atmospheric N_2O in the stratosphere through photolysis and photooxidation (IPCC, 2007).” Citing the 2007 IPCC report, they note “soils have been identified as the main sources for atmospheric N_2O .”

To learn more about the emission of N_2O from wet vs. dry soils, Goldberg and Gebauer induced an artificial summer drought of 46 days duration (which was accompanied by a natural drought) via throughfall exclusion (TE) that was provided by

special roof installations, which they followed with an experimental rewetting of 66 mm over two days, during which periods (and before and after them) they closely monitored N₂O fluxes from the soils of the TE and unaltered control (C) plots that were exposed to the elements.

The two researchers write, “before the drought, both the C and TE plots showed slightly positive N₂O fluxes from the soil to the atmosphere,” in harmony with the sentiment of the IPCC. During the drought, on the other hand, “the soil of both the throughfall exclusion and control plots served as an N₂O sink,” contrary to what might have been expected in light of IPCC statements. They state, “the sink strength of the throughfall exclusion plots was doubled compared with the control plots.” Rewetting “turned the soil into a source for atmospheric N₂O again,” but “it took almost four months to turn the cumulative soil N₂O fluxes from negative (sink) to positive (source) values.” Goldberg and Gebauer conclude, “long drought periods can lead to drastic decreases of N₂O fluxes from soils to the atmosphere or may even turn forest soils temporarily to N₂O sinks,” which may in some places persist for years at a time. It is also possible that over the entire terrestrial surface of the planet, the net result is that “soils are the main sources for atmospheric N₂O,” as stated by the IPCC. Nevertheless, the two scientists conclude that what they call an unbalanced global N₂O budget “underlines the likelihood of a hitherto unconsidered sink function of soils.”

In combining the effects of soil water status and atmospheric CO₂ on N₂O emissions, Welzmler *et al.* (2008) measured N₂O and denitrification emission rates in a C₄ sorghum [*Sorghum bicolor* (L.) Moench] production system with ample and limited flood irrigation rates under free-air CO₂ enrichment (seasonal mean = 579 ppm) and control (seasonal mean = 396 ppm) conditions during the 1998 and 1999 summer growing seasons at the experimental FACE site near Maricopa, Arizona (USA). They found “elevated CO₂ did not result in increased N₂O or N-gas emissions with either ample or limited irrigation,” which they describe as being “consistent with findings for unirrigated western U.S. ecosystems reported by Billings *et al.* (2002) for Mojave Desert soils and by Mosier *et al.* (2002) for Colorado shortgrass steppe.” Welzmler *et al.* say their results suggest “as CO₂ concentrations increase, there will not be major increases in denitrification in C₄ cropping environments such as irrigated sorghum in

the desert southwestern United States,” which further suggests there will not be an increased impetus for global warming due to this phenomenon.

Adding temperature to the mix, Cantarel *et al.* (2011) monitored N₂O fluxes in an *in situ* ecosystem manipulation experiment simulating the climate predicted for the study area (an upland temperate grassland in the French Massif Central region), making use of the Clermont Climate Change Experiment facility, where Bloor *et al.* (2010) were conducting “a long-term grassland study of multiple climate changes applied in an additive experimental design.” Over a two-year period, they monitored N₂O fluxes under conditions “simulating the climate predicted for the study area in 2080 (3.5°C temperature increase, 20% reduction in summer rainfall and atmospheric CO₂ levels of 600 ppm).”

“Overall,” as the four researchers describe the results of their study, “experimental warming had a positive effect on the annual N₂O emissions.” However, and “contrary to expectations,” as they put it, “combined summer drought and warming had no significant effect on mean N₂O fluxes recorded at any time,” nor did “elevated CO₂ in combination with warming and drought.”

Also writing in 2011, Carter *et al.* (2011) note “in temperate regions, climate change is predicted to increase annual mean temperature and intensify the duration and frequency of summer droughts, which together with elevated atmospheric carbon dioxide concentrations, may affect the exchange of nitrous oxide (N₂O) and methane (CH₄) between terrestrial ecosystems and the atmosphere.” Working in a dry, temperate heathland with a nutrient-poor sandy soil located about 50 km northwest of Copenhagen, Denmark—the vegetation of which was dominated by Scotch Heather (*Calluna vulgaris*), Wavy Hairgrass (*Deschampsia flexuosa*), and various mosses—Carter *et al.* set out to investigate “the effects of future climatic and atmospheric conditions on the biosphere-atmosphere exchange of N₂O and CH₄.”

With respect to N₂O emissions (we reported their results with respect to methane earlier), the researchers found “as single experimental factors, elevated CO₂, temperature and summer drought had no major effect on the N₂O fluxes, but the combination of CO₂ and warming stimulated N₂O emission, whereas the N₂O emission ceased when CO₂ was combined with drought.” Carter *et al.* conclude their study “highlights the importance of evaluating climate change parameters in multifactor

treatments as the response of CH₄ and N₂O flux rates to different two- and three-factor combinations may not be predicted from the responses to the individual treatments.” They add, “overall, our study suggests that in the future, CH₄ uptake may increase slightly, while N₂O emission will remain unchanged in temperate ecosystems on well-aerated soils.”

The research reviewed here thus suggests concerns about additional global warming arising from enhanced N₂O emissions from agricultural soils in a CO₂-enriched atmosphere of the future are not well founded.

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2.4 Clouds

Understanding how Earth’s clouds respond to anthropogenic-induced perturbations of the atmosphere is of paramount importance in determining the impact of the ongoing rise in the air’s CO₂ content on global climate. Both naturally occurring and manmade aerosols have a strong influence on cloud albedo (solar reflectance) and

cloud cover, with a global mean thermal forcing estimated to be of approximately the same magnitude as that of mankind's production of greenhouse gases, but of opposite sign.

The following subsections present brief reviews of a number of scientific papers that address these important subjects. Additional information can be found in related subjects treated in this volume, including the inadequacies of climate models in dealing with clouds and the climatic influence of aerosols (see Chapter 1).

2.4.1 Albedo

Perhaps the best-known imputed impact of mankind on climate is the enhancement of the atmosphere's greenhouse effect said to be produced by the carbon dioxide released into the atmosphere by the burning of fossil fuels such as coal, gas, and oil. There are, however, several other ways in which human activities are believed to influence Earth's climate, and many of these phenomena tend to *cool* the globe, primarily by enhancing its albedo, or reflectance of incoming solar radiation.

Ferek *et al.* (1998), for example, observed an increase in the reflectance of solar radiation from clouds exposed to the airborne effluents of ships, while Capaldo *et al.* (1999) determined this phenomenon creates a significant cooling influence over water surfaces in the Northern and Southern Hemispheres. Facchini *et al.* (1999) report organic solutes evolving from agricultural/industrial regions tend to enhance cloud reflectance over land.

Charlson *et al.* (2001) note clouds droplets "are the most important factor controlling the albedo (reflectivity) and hence the temperature of our planet," and manmade aerosols "have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases." Even a small change in cloud properties could determine whether the combined influence of anthropogenic activities results in a net warming or cooling of the planet.

The results of several empirical studies led Charlson *et al.* to conclude the anthropogenic impetus for cooling "may be even larger than anticipated." He and his colleagues point out the early IPCC assessments of the situation "do not include the combined influences of some recently identified chemical factors, each of which leads to additional negative forcing (cooling) on top of that currently estimated." They write, "It has recently become clear

that soluble gases, slightly soluble solutes [aerosols], and surface tension depression by organic substances also influence the formation of cloud droplets." The ways in which mankind's activities influence these processes tend to produce extra cloud cooling power that is nowhere to be found in early IPCC analyses of cloud effects on climate.

Consider, for example, the original hypothesis developed by Charlson *et al.* (1987), which has inspired literally hundreds of subsequent confirmatory studies, wherein biology plays an integral role in mitigating global warming. This scenario begins with an initial impetus for warming that stimulates primary production in marine phytoplankton, which results in the production of more copious quantities of dimethylsulphoniopropionate (DMSP), which leads to the evolution of greater amounts of dimethyl sulphide (DMS) in the surface waters of the world's oceans. The DMS diffuses into the atmosphere, where it is oxidized, which leads to the creation of acidic aerosols that function as cloud condensation nuclei. Those nuclei create more and brighter clouds of higher albedo, which reflect more incoming solar radiation back to space, which cools the planet and thereby counters the initial impetus for warming.

Simo and Pedros-Alio (1999) added even more complexity to this scenario by describing a number of short-term photo-induced (and, therefore, mixing-depth mediated) influences on several complex physiological phenomena manifest in marine phytoplankton, as well as longer-term variations in vertical mixing that influence planktonic succession and food-web structure. Ayers and Gillett (2000) summarized empirical evidence in support of Charlson *et al.*'s hypothesis obtained from data collected at Cape Grim, Tasmania since 1988, as well as from what has been reported in prior studies of the subject. They too conclude there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer."

Sciare *et al.* (2000) made continuous measurements of atmospheric DMS concentration and a number of environmental parameters from 1990 to 1999 at Amsterdam Island in the southern Indian Ocean, finding a clear seasonal variation with a factor of 20 difference in amplitude between the maximum atmospheric DMS concentration in austral summer and the minimum in austral winter. The DMS

anomalies were found to be “closely related to sea surface temperature anomalies, clearly indicating a link between DMS and climate changes.” They found a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50 percent on a monthly basis, providing what they called a “very important” albedo-moderated negative feedback on the original impetus for warming. (DMS will be discussed more thoroughly later in this chapter.)

In addition to DMS, there is COS, carbonyl sulfide, which operates in a somewhat similar albedo-enhancing fashion over land. COS is the most stable and abundant reduced sulfur gas in the atmosphere and a major player in determining Earth’s radiation balance. After making its way into the stratosphere, it can be photo-dissociated, as well as oxidized, to form SO₂, which is typically converted to sulfate aerosol particles that are highly reflective of incoming solar radiation and, therefore, have the capacity to significantly cool Earth. Like DMS, COS is heavily influenced by planetary biology.

In a study of COS uptake by a lichen species found in an open-oak woodland in central California, Kuhn and Kesselmeier (2000) observed the rate of absorption of COS from the atmosphere by this species declined dramatically once air temperature rose above 25°C. Thus, when temperatures begin to become uncomfortably warm for this and many other species of plants (and animals), more COS remains in the air, which increases the potential for more of it to make its way into the stratosphere, where it can be converted into sulfate aerosol particles that can reflect more incoming solar radiation back to space and thereby cool Earth. Since the consumption of COS by lichens is under the physiological control of carbonic anhydrase—the key enzyme for COS uptake in all higher plants, algae, and soil organisms—one could expect this phenomenon to be generally operative over much of the planet, which it is. This biological “thermostat” may be powerful enough to define an upper limit above which the surface air temperature of Earth may be restricted from rising, even when changes in other forcing factors, such as greenhouse gases, produce a substantial impetus for warming. (COS will be discussed more completely later in this chapter.)

That several of the above-described phenomena, as well as others yet to be elucidated, may be occurring at the present time is suggested by the study of Herman *et al.* (2001), who used satellite data to determine changes in radiation reflected back to space

over the period 1979 to 1992. Their data indicate “there have been increases in reflectivity (cloudiness) poleward of 40°N and 30°S, with some smaller but significant changes occurring in the equatorial and lower middle latitudes.” And they state the overall long-term effect is for an increase in radiation reflected back to space of 2.8 W m⁻² per decade, from which they conclude, “there is a likely cooling effect” provided “by changes in the amount of snow/ice, cloudiness, and aerosols.”

One year later, Chou *et al.* (2002) analyzed aerosol optical properties retrieved from the satellite-mounted Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and used them in conjunction with a radiative transfer model of the planet’s atmosphere to calculate the climatic effects of aerosols over Earth’s oceans. They found “aerosols reduce the annual-mean net downward solar flux by 5.4 W m⁻² at the top of the atmosphere, and by 5.9 W m⁻² at the surface.” During the large Indonesian fires of September–December 1997, however, the radiative impetus for cooling at the top of the atmosphere was more than 10 W m⁻², and it was more than 25 W m⁻² at the surface of the sea in the vicinity of Indonesia.

The magnitude of the radiative warming impetus predicted at the start of the global warming controversy to occur in response to a nominal doubling of the air’s CO₂ content is about 4 W m⁻², less than what researchers have found to be the radiative cooling effect of atmospheric aerosols. Thus over the majority of the planet’s surface, the radiative cooling influence of atmospheric aerosols (many of which are produced by anthropogenic activities) likely prevails, suggesting a probable net anthropogenic-induced climatic signal that must be very close to zero and nowhere near capable of producing what the IPCC refers to as the unprecedented warming of the twentieth century.

Breon *et al.* (2002) assessed the effects of atmospheric aerosols around the globe on cloud microphysics via data on aerosol concentration and cloud droplet radii obtained from the polarization and directionality of the Earth reflectances (POLDER) instrument on the Advanced Earth-Observing Satellite (ADEOS), which began operation on 30 October 1996 and ended on 30 June 1997. In their words, the study’s results “clearly demonstrate a significant impact of aerosols on cloud microphysics.” As aerosol concentrations increased, cloud droplet radii decreased, which should produce a cooling influence due to the greater albedo generally associated with smaller cloud droplets. The researchers also

determined “the bulk of the aerosol load originates from slash-and-burn agriculture practices and from highly polluted areas,” such that “a large fraction of the observed aerosol effect on clouds is probably of anthropogenic origin.”

Although Breon *et al.* were unable to quantify the degree of cooling provided by the presence of the aerosols they studied, they nevertheless concluded this anthropogenic counterforce to the warming impetus provided by the ongoing rise in the air’s CO₂ content is “significant and occurs on a global scale.”

Several natural and anthropogenic-induced negative feedbacks clearly are capable of maintaining the climate of the globe within a temperature range conducive to the continued well-being of all forms of life on Earth. Many of these feedbacks have yet to receive the attention they merit from the IPCC.

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2.4.2 Cloud Cover

In addition to cloud albedo, the reaction of cloud cover to anthropogenic-induced changes in the atmosphere is an important part of the discussion over how climate will be affected by an ongoing rise in the air’s carbon dioxide content. Here we review scientific papers that address this topic.

Ferek *et al.* (1998) determined cloud condensation nuclei in the airborne effluents of ships off the west coast of the United States were responsible for producing ship tracks—brighter and more persistent streaks in the overlying layer of natural and less-reflective cloud, both of which exert a cooling influence during daylight hours. Similarly, based on what is known about the properties of the aerosols responsible for jet aircraft contrails, Meerkotter *et al.* (1999) suggest the presence of such contrails tends to cool Earth’s surface during daylight hours but warm it at night. They also note aircraft emissions may cause additional indirect climate forcing by changing the particle size of natural cirrus clouds, concluding “this indirect forcing may be comparable to the direct forcing due to additional contrail cloud cover.”

Boucher (1999) and Nakanishi *et al.* (2001) both find aircraft-induced increases in high-cloud amount may also have a warming effect, although Charlson *et al.* (2001) contend the net effect of all anthropogenic-

produced aerosols averaged over the globe is a cooling.

Facchini *et al.* (1999) studied the effects of atmospheric solutes collected from cloud water in the Po Valley of Italy. They found water vapor was more likely to form on its organic-solute-affected aerosols of lower surface tension—as opposed to the less-organic-solute-affected aerosols of the natural environment with their higher surface tension—creating more, smaller, and therefore more highly reflective cloud droplets, which tend to cool the local environment. They also observed the organic fractions and concentrations of the aerosols they studied were similar to those found in air downwind of other large agricultural/industrial regions, hinting at the likely widespread occurrence of this human-induced cooling influence.

Studying this phenomenon several years earlier, Kulmala *et al.* (1993) noted “it is likely that the smaller droplet size will decrease precipitation so that the clouds will have a longer lifetime.” In addition, they observed “cloud formation can take place at smaller saturation ratios of water vapor” in the presence of organic-solute-affected aerosols, suggesting clouds will be able to form earlier and in places where they would not otherwise form. In response to this particular type of anthropogenic effluent, therefore, cloud lifetimes expand at both ends—they are born earlier and die later, so to speak.

How significant are these phenomena? Leaitch *et al.* (1992) conclude the increased radiative cooling power due only to the increase in cloud albedo that results from pollution-induced increases in cloud droplet concentration averages about 2 W m^{-2} over North America, about half the radiative warming power typically predicted to accompany a nominal doubling of the air’s CO_2 content. Adding the impact of increased cloud cover likely would make the overall effect considerably greater.

Satheesh and Ramanathan (2000) measured the clear-sky radiative consequences of the December-to-April northeastern low-level monsoonal flow of air that transports sulphates, nitrates, organics, soot, and fly ash (among other anthropogenically produced substances) from the Indian subcontinent and southern Asia thousands of kilometers over the north Indian Ocean and as far south as 10°S latitude. They found the “mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to 30 W m^{-2} ,” which Schwartz and Buseck (2000) point out is “three to seven times as great as global average longwave (infrared) radiative

forcing by increases in greenhouse gases over the industrial period ... but opposite in sign.”

This finding was somewhat tempered by the study of Ackerman *et al.* (2000), who suggest the large cooling effect likely was counterbalanced by a simultaneous reduction in cloud cover. But in an analysis of a long-term study of real-world data, Norris (2001) proved that suggestion to be wrong, reaffirming the overall implications of the Satheesh and Ramanathan study.

Norris reasoned that if the conclusion of Ackerman *et al.* was correct, the great increase in anthropogenic aerosol emissions from southern and southeast Asia over the past half-century should have significantly decreased the low-level cloud cover over the northern Indian Ocean during this period. A test of this idea with data from the Extended Edited Cloud Report Archive, however, revealed daytime low-level cloud cover over this part of the world in fact increased, and it did so in both the Northern and Southern Hemispheric regions of the study area and at essentially all hours of the day.

Croke *et al.* (1999) determined the mean cloud cover of three regions of the United States (coastal southwest, coastal northeast, and southern plains) rose from 35 percent to 47 percent from 1900 to 1987, while global mean air temperature rose by approximately 0.5°C . Similarly, Chernykh *et al.* (2001) determined global cloud cover rose by nearly 6 percent between 1964 and 1998. These observations suggest Earth’s hydrologic cycle does indeed tend to moderate the thermal effects of any impetus for warming and, as noted by the latter authors, is “consistent with the decrease in diurnal temperature range evident over most of the globe.”

Another way by which clouds tend to stabilize Earth’s climate was suggested by Sud *et al.* (1999). Based on data from the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, these investigators found deep convection in the tropics acts as a thermostat to keep vacillation of sea surface temperature (SST) within a rather narrow range. Starting at the low end of the range, the tropical ocean acts as a net receiver of energy and warms. Soon thereafter, however, the cloud-base airmass is charged with the moist static energy needed for clouds to reach the upper troposphere, and the cloud cover thus formed reduces the amount of solar radiation received at the sea surface, while its cool and dry downdrafts also tend to promote surface cooling. This “thermostat-like control,” as Sud *et al.* put it, tends to “ventilate the

tropical ocean efficiently and help contain the SST between 28–30°C.”

Lindzen *et al.* (2001) described another mechanism through which tropical ocean temperatures may be constrained by cloud-mediated phenomena. Based on upper-level cloudiness data obtained from the Japanese Geostationary Meteorological Satellite and SST data obtained from the National Centers for Environmental Protection, these researchers determined the cloudy moist region of the eastern part of the tropical western Pacific “appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature.” The strong inverse relationship they found between upper-level cloud area and mean SST was determined to be sufficient to “more than cancel all the positive feedbacks in the more sensitive current climate models.”

Plant life also plays an important role in stabilizing climate. The pioneering paper of Charlson *et al.* (1987), for example, describes how an initial SST increase leads to increased phytoplanktonic productivity in Earth’s oceans, which leads to a greater sea-to-air flux of dimethyl sulfide (DMS), which undergoes a gas-to-particle conversion that leads to greater numbers of cloud condensation nuclei that create more and brighter clouds that reflect more incoming solar radiation back to space, thereby countering the initial impetus for warming. Subsequently, Ayers and Gillett (2000) reviewed what had been learned in the following years, concluding “major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis,” additionally noting there is “compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere.”

Further support for the powerful negative feedback loop is provided by Simo and Pedros-Alio (1999), who studied the effect of the depth of the surface mixing-layer on DMS production. (For a more complete discussion of DMS, see the section on Dimethylsulfide, this chapter.)

Although studies of real-world phenomena continue to clarify the workings of the planet’s climate system and improve our understanding of it, computer models have a difficult time capturing the

system’s complexities. Groisman *et al.* (2000), for example, evaluated the ability of several climate models to reproduce mean daily cloud-temperature relations at different times of year. Although most models did a good job in the cold part of the year, “large discrepancies between empirical data and some models are found for summer conditions.” The overall cloud effect on summer near-surface air temperature computed by one of the models was of the wrong sign.

In another study, Gordon *et al.* (2000) examined the response of a coupled general circulation model of the atmosphere to quasi-realistic specified marine stratocumulus clouds and compared the results to what they obtained from their model when operating in its normal mode, which fails to adequately express the presence of the clouds and their effects. When they removed the low clouds, as occurs in the model’s normal application, the sea surface temperature warmed by fully 5.5°C.

Two years later, two data-based studies published in *Science*—Chen *et al.* (2002) and Wielicki *et al.* (2002)—revealed what Hartmann (2002) called a pair of “tropical surprises.” The first of the seminal discoveries was the finding of both Chen *et al.* and Wielicki *et al.* that the amount of thermal radiation emitted to space at the top of the tropical atmosphere increased by about 4 W m⁻² between the 1980s and the 1990s; the second was that the amount of reflected sunlight decreased by 1 to 2 W m⁻² over the same period, with the net result that more total radiant energy exited the tropics in the latter decade.

These changes were significant. The measured thermal radiative energy loss at the top of the tropical atmosphere, for example, was of the same magnitude as the thermal radiative energy gain generally predicted for a doubling of the air’s CO₂ content. Yet as Hartman noted, “only very small changes in average tropical surface temperature were observed during this time.” So what went wrong—or more correctly, what went right?

For one, the competing change in solar radiation reception driven by changes in cloud cover allowed more solar radiation to reach the surface of Earth’s tropical region and warm it. These changes were produced by what Chen *et al.* determined to be “a decadal-time-scale strengthening of the tropical Hadley and Walker circulations.” Moreover, the past quarter-century’s slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean, recently reported by

McPhaden and Zhang (2002), would have promoted tropical sea surface warming by reducing the rate of supply of relatively colder water to the region of equatorial upwelling.

These observations provide several new phenomena for the models to replicate as a test of their ability to properly represent the real world. McPhaden and Zhang note, for example, the meridional overturning circulation of the upper Pacific Ocean provides “an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific.” If the climate models cannot reconstruct this simple wind-driven circulation, it is difficult to be confident in their projections.

In an application of this principle, Wielicki *et al.* (2002) tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. No significant decadal variability was exhibited by any of the models, and all were unable to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test conclude “the missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved.” Hartmann is more candid in his scoring of the test, saying it indicates “the models are deficient.” He notes, “if the energy budget can vary substantially in the absence of obvious forcing,” as it did over the prior two decades, “then the climate of Earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models.” (Additional discussion of climate models’ treatment of clouds can be found in Chapter 1.)

Fu *et al.* (2002) and Hartmann and Michelsen (2002) continued to chip away at the adaptive infrared iris concept of Lindzen *et al.* (2001). Fu *et al.* argue “the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive,” while also claiming to show water vapor and low cloud effects are overestimated by Lindzen *et al.* by at least 60 percent and 33 percent, respectively. Fu and his colleagues obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al.*’s larger negative feedback factor of -0.45 to -1.03.

Chou *et al.* (2002) responded, suggesting Fu *et*

al.’s approach of specifying longwave emission and cloud albedos “appears to be inappropriate for studying the iris effect.” They note, “thin cirrus are widespread in the tropics and ... low boundary clouds are optically thick,” and “the cloud albedo calculated by [Fu *et al.*] is too large for cirrus clouds and too small for boundary layer clouds,” so that “the near-zero contrast in cloud albedos derived by [Fu *et al.*] has the effect of underestimating the iris effect.” Chou *et al.* ultimately agreed Lindzen *et al.* “may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al.*].”

Two years later, Minnis *et al.* (2004) analyzed surface-based measurements of cirrus coverage (CC) for different parts of the world for the period 1971–1995 while employing similar measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) for 1984–1996 as a consistency check. The linear trends they derived from the data were input to a relationship between changes in cirrus amount and surface temperature (derived from a general circulation model of the atmosphere) in order to calculate their climatic impact over the United States.

Minnis *et al.* report “values of CC increased over the United States, the North Atlantic and Pacific, and Japan, but dropped over most of Asia, Europe, Africa, and South America,” noting “the largest concentrated increases occurred over the northern Pacific and Atlantic and roughly correspond to the major air traffic routes.” Their U.S. temperature assessment additionally indicates “the cirrus trends over the United States are estimated to cause a tropospheric warming of 0.2°–0.3°C per decade, a range that includes the observed tropospheric temperature trend of 0.27°C per decade between 1975 and 1994.” Those results suggest nearly all of the surface warming observed over the United States between 1975 and 1994, which they reported to be 0.54°C, may have been due to aircraft-induced increases in cirrus cloud cover and not the increase in the air’s CO₂ content over that period.

Harrison and Stephenson (2005) reasoned that because the net global effect of clouds is cooling (Hartmann, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, just as local overcast conditions can do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF) measured daily at 0900 UT at Whiteknights, Reading (UK) in 1997–2004 with the traditional subjective determination of cloud amount made simultaneously

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by a human observer as well as with daily average temperature. They then compared the DF measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux.

Their work revealed “across the UK, on days of high cosmic ray flux (above 3600×10^2 neutron counts per hour, which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by $19\% \pm 4\%$, and (ii) the diffuse fraction increases by $2\% \pm 0.3\%$.” In addition, they found “during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction,” and they note the latter of these observations indicates diffuse radiation changes are, indeed, “unambiguously due to cosmic rays.” They further report, “at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR” and suggest the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima. They note, “this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al.*, 2003) which neglect a cosmic ray effect.” In addition, although the effect they detect is small, they state it is “statistically robust” and the cosmic ray effect on clouds likely “will emerge on long time scales with less variability than the considerable variability of daily cloudiness.”

The following year, Palle *et al.* (2006) used the most up-to-date cloud cover data from the International Satellite Cloud Climatology Project and, following the protocols of Palle *et al.* (2004), derived globally averaged albedo anomalies and related solar radiative forcing anomalies experienced by Earth over the prior two decades. In addition, the four researchers explored the effects on total radiative forcing (solar plus thermal) of observed changes in the amounts of low-, high-, and mid-level clouds that occurred between 2000 and 2004.

Between 1985 and 2000, Palle *et al.* calculated, the flux of solar radiation absorbed by the Earth-atmosphere system rose by about 8 W m^{-2} in response to an observed decline in total cloud amount. Thereafter, total cloud amount began to rise, but because of a concomitant redistribution of cloud types (an increase in high- and mid-level clouds that tend to

warm the planet, and a decrease in low-level clouds that tend to cool the planet), they conclude the positive radiative forcing trend experienced between 1985 and 2000 may have continued to the time of the writing of their paper, even in the face of an increasing total cloud amount.

Palle *et al.* note the increase in radiative forcing produced by the increasing atmospheric concentrations of all greenhouse gases since 1850 was roughly 2.5 W m^{-2} . Compared to the increase in radiative forcing that may have been experienced between 1985 and 2005 as a result of observed changes in total cloud amount and the fractions of clouds located at different elevations ($\sim 11 \text{ W m}^{-2}$, according to the data and analyses of Palle *et al.*), the 20-year change in radiative forcing due to CO_2 alone would have been truly minuscule, suggesting the angst manifest over anthropogenic CO_2 emissions may be misplaced. And if a radiative forcing of $\sim 11 \text{ W m}^{-2}$ raised mean global air temperature by only a fraction of a degree, as occurred between 1985 and 2005, it would appear Earth’s climate is much less responsive to changes in radiative forcing than the IPCC and most climate modelers claim it to be.

One additional study merits discussion here. Based on approximately 185 million synoptic weather observations obtained from 5,400 stations worldwide, covering all continents and many islands, Warren *et al.* (2007) developed separate day and night histories of cloud amount for nine cloud types for the 26-year period 1971–1996. This work revealed, “there are large regional changes in cloud-type amounts, and significant changes in the global averages of some cloud types.” More specifically, they state “the time series of total-cloud-cover anomalies for individual continents show a large decrease for South America, small decreases for Eurasia and Africa, and no trend for North America.” They also observe “the zonal average trends of total cloud cover are positive in the Arctic winter and spring, 60° – 80°N , but negative in all seasons at most other latitudes.” In addition, they state “night trends agree with day trends for total cloud cover and for all cloud types except cumulus,” and “cirrus trends are generally negative over all continents.” They found these changes “compensate each other to result in only a small trend of global average land cloud cover, $-0.7\% \text{ decade}^{-1}$.” In addition, they note “this small negative trend is further compensated by a small positive trend over the ocean of $+0.4\% \text{ decade}^{-1}$ (Norris, 1999), resulting in almost no trend for global average cloud cover over

the past few decades.”

Although Warren *et al.* acknowledged the significance of changes in cloud type and amount for global and regional climate change and vice versa, they did not speculate on the climatic implications of their findings, noting “it will be important to prepare cloud datasets for the more recent years [post 1996], when changes may become more noticeable with increased global warming.”

The IPCC claims in AR5 that “the net radiative feedback due to all cloud types is likely positive” (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, as shown in this section and the preceding section of this chapter, substantial research indicates the net global effect of cloud feedbacks is one of cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.

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2.5 Aerosols

Aerosols are an important factor in global temperature because they affect Earth's energy budget through their ability to reflect and scatter light and their propensity to absorb and radiate thermal radiation. In its *Fifth Assessment Report* (AR5), the IPCC concludes “the total aerosol effect is estimated as [a radiative forcing] of -0.7 and [an adjusted forcing] of -0.9 W m⁻²” (p. 8-4 of Chapter 8, Second Order Draft of AR5, dated October 5, 2012). Such estimates were revised downward (a less-negative feedback) from the IPCC's *Fourth Assessment Report*, but as demonstrated in this section, many studies indicate aerosols are capable of producing a much stronger cooling effect, thus calling into question the IPCC's decision to downgrade the strength of this negative feedback. Several studies suggest the radiative forcing of aerosols may be as large as, or larger than, the radiative forcing due to atmospheric CO₂.

Our review of aerosol studies begins with an analysis of the total aerosol effect on climate, followed by a separate discussion of four important aerosol categories: (1) Biological (Aquatic), (2) Biological (Terrestrial), (3) Non-Biological (Anthropogenic), and (4) Non-Biological (Natural).

2.5.1 Total Aerosol Effect

Ghan *et al.* (2001) studied the positive radiative forcings of greenhouse gases and the negative radiative forcings of anthropogenic aerosols, reporting current best estimates of “the total global mean present-day anthropogenic forcing range from 3 W m⁻² to -1 W m⁻²,” which represents everything from a modest warming to a slight cooling. After performing their own analysis, they reduced the range somewhat but found it still stretched from a small cooling influence to a modest impetus for warming. “Clearly,” they conclude, “the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies.”

Vogelmann *et al.* (2003) point out “mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR [infrared] flux between 7 and 25 W m⁻² (Sokolik *et al.*, 1998).” They note “only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing.” The

researchers used high-resolution spectra to obtain the IR radiative forcing at Earth's surface for aerosols encountered in the outflow from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer from the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. They determined "daytime surface IR forcings are often a few W m^{-2} and can reach almost 10 W m^{-2} for large aerosol loadings." These values, in their words, "are comparable to or larger than the 1 to 2 W m^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times" and "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

Similar findings were reported by Chou *et al.* (2002), who analyzed aerosol optical properties retrieved from the satellite-mounted Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and used them in conjunction with a radiative transfer model of the planet's atmosphere to calculate the climatic effects of aerosols over Earth's major oceans. In general, this effort revealed "aerosols reduce the annual-mean net downward solar flux by 5.4 W m^{-2} at the top of the atmosphere, and by 5.9 W m^{-2} at the surface." During the large Indonesian fires of September-December 1997, however, the radiative impetus for cooling at the top of the atmosphere was more than 10 W m^{-2} , while it was more than 25 W m^{-2} at the surface of the sea in the vicinity of Indonesia.

Wild (1999) used a comprehensive set of collocated surface and satellite observations to calculate the amount of solar radiation absorbed in the atmosphere over equatorial Africa and compared the results with the predictions of three general circulation models of the atmosphere. The climate models did not properly account for spatial and temporal variations in atmospheric aerosol concentrations, leading them to predict regional and seasonal values of solar radiation absorption in the atmosphere with underestimation biases of up to 30 W m^{-2} . By way of comparison, as noted by Vogelmann *et al.*, the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times is 1 to 2 W m^{-2} .

Aerosol uncertainties and the problems they generate figure prominently in a study by Anderson *et al.* (2003), who note there are two different ways by which the aerosol forcing of climate may be computed. The first is forward calculation, based, in their words, on "knowledge of the pertinent aerosol

physics and chemistry." The second approach is inverse calculation, based on "the total forcing required to match climate model simulations with observed temperature changes."

The first approach utilizes known physical and chemical laws and assumes nothing about the outcome of the calculation. The second approach, in considerable contrast, is based on matching residuals, where the aerosol forcing is computed from what is required to match the calculated change in temperature with the observed change over some period of time. Consequently, in the words of Anderson *et al.*, "to the extent that climate models rely on the results of inverse calculations, the possibility of circular reasoning arises."

Which approach do climate models typically employ? "Unfortunately," Anderson *et al.* write, "virtually all climate model studies that have included anthropogenic aerosol forcing as a driver of climate change have used only aerosol forcing values that are consistent with the inverse approach." Anderson *et al.* report the negative forcing of anthropogenic aerosols derived by forward calculation is "considerably greater" than that derived by inverse calculation; if forward calculation is employed, the results "differ greatly" and "even the sign of the total forcing is in question." This implies "natural variability (that is, variability not forced by anthropogenic emissions) is much larger than climate models currently indicate," they write. Anderson *et al.* conclude, "inferences about the causes of surface warming over the industrial period and about climate sensitivity may therefore be in error."

Schwartz (2004) also addressed the subject of uncertainty as it applies to the role of aerosols in climate models. Noting the National Research Council (1979) concluded "climate sensitivity [to CO_2 doubling] is likely to be in the range $1.5\text{--}4.5^\circ\text{C}$ " and "remarkably, despite some two decades of intervening work, neither the central value nor the uncertainty range has changed," Schwartz opines this continuing uncertainty "precludes meaningful model evaluation by comparison with observed global temperature change or empirical determination of climate sensitivity" and "raises questions regarding claims of having reproduced observed large-scale changes in surface temperature over the 20th century."

Schwartz thus contends climate model predictions of CO_2 -induced global warming "are limited at present by uncertainty in radiative forcing of climate change over the industrial period, which is dominated by uncertainty in forcing by aerosols," and if this

situation is not improved, “it is likely that in another 20 years it will still not be possible to specify the climate sensitivity with [an] uncertainty range appreciably narrower than it is at present.” He adds, “the need for reducing the uncertainty from its present estimated value by at least a factor of 3 and perhaps a factor of 10 or more seems inescapable if the uncertainty in climate sensitivity is to be reduced to an extent where it becomes useful for formulating policy to deal with global change.”

Lubin and Vogelmann (2006) employed five multisensor radiometric data sets from the North Slope of Alaska to study how enhanced concentrations of anthropogenic aerosols originating from industrial regions of lower latitudes alter the microphysical properties of Arctic clouds via a process known as the first indirect effect of aerosols. They determined this phenomenon operates in low optically thin single-layered Arctic clouds, producing an increase in the downwelling flux of longwave (thermal) radiation. Under frequently occurring cloud types, they found anthropogenic aerosols regularly advected into the Arctic lead to an average increase of 3.4 W m^{-2} in the downward-directed thermal radiation flux at Earth’s surface. The two researchers state “the observed longwave enhancement has climatological significance.”

The work of Charlson *et al.* (2005) supports that assessment. They report the longwave radiative forcing provided by all greenhouse gas increases since the beginning of the industrial era amounts to 2.4 W m^{-2} , citing the work of Anderson *et al.* (2003). Similarly, Palle *et al.* (2004) state “the latest IPCC report argues for a 2.4 W m^{-2} increase in CO_2 longwave forcing since 1850.” Consequently, if the calculations of Lubin and Vogelmann are correct, the longwave radiative forcing of the anthropogenic aerosols that are advected into the Arctic may be larger than the combined forcing of all greenhouse gas increases since the beginning of the industrial era, suggesting recent increases in anthropogenic aerosol emissions could be the primary source of whatever Arctic warming may have occurred in recent years.

Jaenicke *et al.* (2007) reviewed the status of research being conducted on biological materials in the atmosphere, which they denominate primary biological atmospheric particles or PBAPs. Originally, these particles were restricted to culture-forming units, including pollen, bacteria, mold, and viruses, but they also include fragments of living and dead organisms and plant debris, human and animal

epithelial cells, broken hair filaments, parts of insects, shed feather fractions, etc., which they lumped together under the category of “dead biological matter.”

With respect to the meteorological and climatic relevance of these particles, Jaenicke *et al.* note many PBAPs, including “decaying vegetation, marine plankton and bacteria are excellent ice nuclei,” and “one can easily imagine the [IR] influence on cloud cover, climate forcing and feedback and global precipitation distribution.”

In describing their own measurements and those of others, which they said “have now been carried out at several geographical locations covering all seasons of the year and many characteristic environments,” Jaenicke *et al.* report, “by number and volume, the PBAP fraction is ~20 percent of the total aerosol, and appears rather constant during the year.” In addition, they write “the impression prevails that the biological material, whether produced directly or shed during the seasons, sits on surfaces, ready to be lifted again in resuspension.”

In a brief summation of their findings, the German researchers state “the overall conclusion can only be that PBAPs are a major fraction of atmospheric aerosols, and are comparable to sea salt over the oceans and mineral particles over the continents.” Consequently, they note, “the biosphere must be a major source for directly injected biological particles, and those particles should be taken into account in understanding and modeling atmospheric processes.” They further note “the IPCC-Report of 2007 does not even mention these particles” and “this disregard of the biological particles requires a new attitude.”

Ramanathan *et al.* (2007) point out light-absorbing and light-scattering aerosols “contribute to atmospheric solar heating and surface cooling,” and “the sum of the two climate forcing terms—the net aerosol forcing effect—is thought to be negative and may have masked as much as half of the global warming attributed to the recent rapid rise in greenhouse gases.” They caution there is “at least a fourfold uncertainty in the aerosol forcing effect.”

Ramanathan *et al.* studied this phenomenon as it has never been studied before, using “three lightweight unmanned aerial vehicles that were vertically stacked between 0.5 and 3 km over the polluted Indian Ocean.” The unmanned vehicles “deployed miniaturized instruments measuring aerosol concentrations, soot amount and solar fluxes”

within the atmospheric brown clouds (ABCs) demonstrated to envelop “most of Asia and the adjacent oceans” during “the six-month-long tropical dry season,” when “convective coupling between the surface and the troposphere is weak [and] aerosol solar heating can amplify the effect of greenhouse gases in warming the atmosphere while simultaneously cooling the surface.” The seven scientists report finding “atmospheric brown clouds enhanced lower atmospheric solar heating by about 50 per cent” during the period of their study. Over the Indian Ocean and Asia during the long tropical dry season, they conclude, general circulation model simulations suggest “atmospheric brown clouds contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends.”

Vautard *et al.* (2009) analyzed the frequency of occurrence of low horizontal visibility conditions over the past three decades at 342 meteorological stations scattered throughout Europe at 0300, 0900, 1500, and 2100 Universal Time, comparing their results with concomitant changes in near-surface air temperature and with spatial and temporal variations in sulfur dioxide emissions. “By enabling less energy to be received at the surface during daytime,” they point out, “the low-visibility phenomenon inhibits surface heating, and therefore induces a lower local temperature.” Since low-visibility conditions were presumed to have declined over the three-decade period due to the implementation of more effective air pollution control measures, the researchers anticipated a warming trend would be evident in the temperature data.

The three researchers document “a massive decline (about 50% in 30 years) of low-visibility occurrence throughout Europe,” and they report this decline was “spatially and temporally correlated with trends in sulfur dioxide emissions, suggesting a significant contribution of air-quality improvements” to the improvement in visibility. By statistically linking local visibility changes with temperature variations, they found “the reduction in low-visibility conditions could have contributed on average to about 10–20% of Europe’s recent daytime warming and to about 50% of eastern European warming.”

The work of Vautard *et al.* (2009) strongly suggests the cleaning-up of European air pollution over the past three decades has been responsible for much of that region’s recent warming, and it is likely that effect has been seen elsewhere around the globe as well. Their findings also provide support for an

urban heat island effect other researchers suggest has inflated the global temperature record.

Mischenko *et al.* (2007) presented a plot of the global monthly average of the column aerosol optical thickness (AOT) of the atmosphere that stretches from August 1981 to June 2005, which they developed from “the longest uninterrupted record of global satellite estimates of the column AOT over the oceans, the Global Aerosol Climatology Project (GACP) record.” This record was derived from “the International Satellite Cloud Climatology Project (ISCCP) DX radiance data set,” which is “composed of calibrated and sampled Advanced Very High Resolution Radiometer radiances.”

As shown in Figure 2.5.1.1, “the green line reveals a long-term decreasing tendency in the tropospheric AOT,” such that “the resulting decrease in the tropospheric AOT during the 14-year period [1991–2005] comes out to be 0.03.” This trend, they note, “is significant at the 99% confidence level.” They explain “observations of downward solar radiation fluxes at Earth’s surface have shown a recovery from the previous decline known as global ‘dimming’, with the ‘brightening’ beginning around 1990.” Their AOT record harmonizes with these observations as well as with estimated trends in primary anthropogenic emissions of SO₂ and black carbon, which they said are known to “contribute substantially to the global AOT.”

These facts raise serious questions about attributions of late-twentieth-century global warming to the increase in the atmosphere’s CO₂ concentration. As noted by Stanhill (2007), changes in the flux of solar radiation received at the surface of Earth as a consequence of the global dimming and brightening phenomena far exceed the changes in longwave radiative forcing produced by historical changes in the air’s CO₂ content. These observations would appear to relegate anthropogenic CO₂ emissions to a much less important role in terms of their ability to elicit significant changes in Earth’s surface temperature.

The IPCC and others contend recent global brightening is merely allowing CO₂-induced warming to become more evident, which enables them to further contend the CO₂ greenhouse effect is actually much stronger than originally believed, having been masked for some time by the cooling power of the prior buildup of the great aerosol load of the atmosphere. Consequently, proponents of the theory of CO₂-induced global warming, such as *Science* magazine’s Richard Kerr, are found writing news

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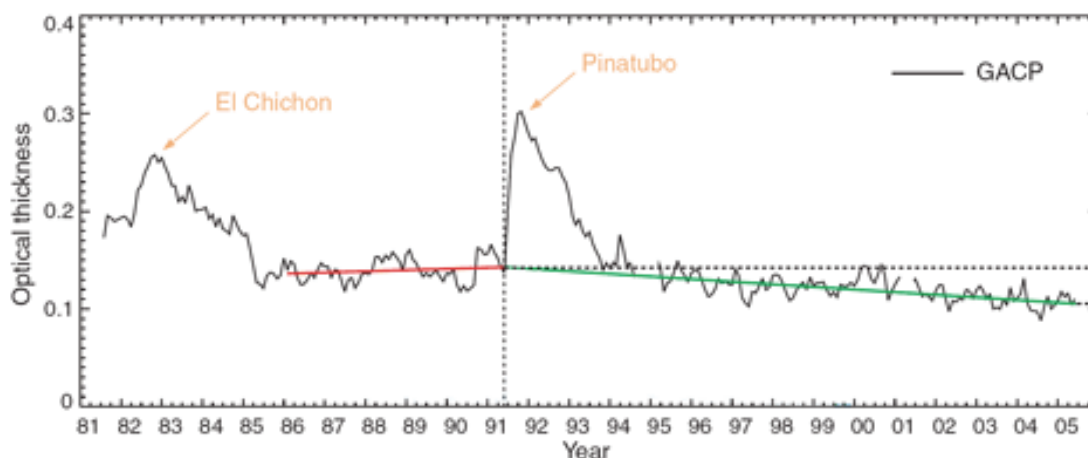


Figure 2.5.1.1. The GACP record of the globally averaged column AOT over the world's oceans. Adapted from Mishchenko, M.I., Geogdzhayev, I.V., Rossow, W.B., Cairns, B., Carlson, B.E., Lacis, A.A., Liu, L., and Travis, L.D. 2007. Long-term satellite record reveals likely recent aerosol trend. *Science* **315**: 1543.

items with titles that ask, “Is a thinning haze unveiling the real global warming?” (Kerr, 2007), when a better question to ask (or at least a reasonable alternative) might have been, “Is a thinning haze revealing its own great power to warm Earth?” Such writers seem to have no trouble finding scientists willing to cast doubt on what they perceive to be the disturbing implications of the unfolding aerosol work. In the case of Kerr’s article, the doubter was Sarah Doherty of the University of Washington, who says there’s simply too much uncertainty in the aerosol data and the problem lies, in part, “in stringing together records from five different instruments flown on five different satellites over the years.”

As if anticipating such an attack, Mishchenko *et al.* clearly state “the successful validation of GACP retrievals using precise Sun photometer data taken from 1983 through 2004 indicates that the ISCCP radiance calibration is likely to be reliable,” and they further note “this conclusion is reinforced by the close correspondence of calculated and observed top of atmosphere solar fluxes.” What is more, they state, “the GACP AOT record appears to be self-consistent, with no drastic intra-satellite variations, and is consistent with the Stratospheric Aerosol and Gas Experiment record.”

Mishchenko *et al.* present ample reason to suspect a significant portion of the observed warming of the twentieth century may have been caused not by increasing atmospheric CO₂ concentrations, but by the increase in surface heating provided by the atmosphere’s declining aerosol optical thickness.

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2.5.2 Biological

In a Research Front article in *Environmental Chemistry*, Jaenicke *et al.* (2007) reviewed the status of research being conducted on biological materials in the atmosphere, which they denominated primary biological atmospheric particles or PBAPs. Originally, these particles were restricted to culture

forming units, including pollen, bacteria, mold, and viruses, but they also include fragments of living and dead organisms and plant debris, human and animal epithelial cells, broken hair filaments, parts of insects, shed feather fractions, etc., which Jaenicke *et al.* (2007) categorized as dead biological matter.

With respect to the meteorological and climatic relevance of these particles, they note many PBAPs, including “decaying vegetation, marine plankton and bacteria are excellent ice nuclei”; “one can easily imagine [their] influence on cloud cover, climate forcing and feedback and global precipitation distribution,” they write.

In describing their own measurements and those of others, which they said “have now been carried out at several geographical locations covering all seasons of the year and many characteristic environments,” Jaenicke *et al.* report “by number and volume, the PBAP fraction is ~20% of the total aerosol, and appears rather constant during the year.” The German researchers added, “the impression prevails that the biological material, whether produced directly or shed during the seasons, sits on surfaces, ready to be lifted again in resuspension.” They conclude “PBAPs are a major fraction of atmospheric aerosols, and are comparable to sea salt over the oceans and mineral particles over the continents”; consequently, “the biosphere must be a major source for directly injected biological particles, and those particles should be taken into account in understanding and modeling atmospheric processes.” They note “the IPCC-Report of 2007 does not even mention these particles” and “this disregard of the biological particles requires a new attitude.”

As research summarized in the following two subsections demonstrates, biologically induced aerosols act as very real and significant feedbacks to global warming. The IPCC’s “new attitude” must include a willingness to acknowledge that current climate models fail to capture many important forcings and feedbacks. When that which is missing is factored in and properly modeled, conclusions radically different from those currently offered by the IPCC are likely.

Others have come to this conclusion. The international team of scientists of Fuzzi *et al.* (2006)—researchers from Finland, Germany, Greece, Italy, Japan, Switzerland, and the United States—found “in spite of impressive advances in recent years ... our understanding of organic aerosol composition, physical and chemical properties, sources, transformation and removal characteristics is very limited,

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and estimates of their actual environmental effects are highly uncertain.” They conclude, “a comprehensive characterization and mechanistic understanding of particle sources, properties, and transformation is required for quantitative assessment, reliable prediction, and efficient control of natural and anthropogenic aerosol effects on climate,” and they identify a host of related “outstanding issues for future research.”

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2.5.2.1 Aquatic

Perhaps the most researched aquatic aerosol feedback loop is the multistage negative feedback phenomenon involving dimethylsulfide, described many years ago by Charlson *et al.* (1987). In the ensuing years, much research has been conducted supporting various stages of this phenomenon, the topic of discussion in subsection 2.5.2.1.1 below.

But other biological aerosols of aquatic origin also have been shown by scientists to have the ability to significantly influence climate. The work of O’Dowd *et al.* (2002) describes one such feedback that by itself may have the capacity to thwart the CO₂ greenhouse effect.

Writing about the O’Dowd *et al.* research in a companion “news and views” article in *Nature*, Kolb (2002) noted the researchers had discovered “a previously unrecognized source of aerosol particles” by unraveling “a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides.”

O’Dowd *et al.* used a smog chamber operated under coastal atmospheric conditions to demonstrate “new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae.” With the help of aerosol formation models, they also

demonstrated concentrations of condensable iodine-containing vapors over the open ocean “are sufficient to influence marine particle formation.”

The aerosol particles O’Dowd *et al.* discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet. With respect to the negative feedback nature of this phenomenon, O’Dowd *et al.* cite the work of Laturnus *et al.* (2000), who demonstrated emissions of iodocarbons from marine biota “can increase by up to 5 times as a result of changes in environmental conditions associated with global change.” As O’Dowd *et al.* note, “increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20–60%” and “changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global radiative forcing similar in magnitude, but opposite in sign, to the forcing induced by greenhouse gases.”

Two years later and working with a different set of coauthors (O’Dowd *et al.*, 2004), O’Dowd measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms. In the winter, when biological activity was at its lowest, the research team found the organic fraction of the submicrometer aerosol mass was about 15 percent. In spring through autumn, when biological activity was high, they found “the organic fraction dominates and contributes 63% to the submicrometer aerosol mass (about 45% is water-insoluble and about 18% water-soluble).” O’Dowd *et al.* then performed model simulations indicating the marine-derived organic matter “can enhance the cloud droplet concentration by 15% to more than 100% and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota.”

Such findings, the researchers state, “completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models.” They add, “an important source of organic matter from the ocean is omitted from current climate-modelling predictions and should be taken into account.”

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- 2.5.2.1.1 Dimethylsulfide
- According to the latest IPCC report, “there is *medium confidence* for a weak feedback involving dimethyl sulfide (DMS), cloud condensation nuclei (CCN), and cloud albedo due to a weak sensitivity of CCN population to changes in DMS emissions” (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). A review of the scientific literature, however, reveals the strength of this negative feedback is likely much larger than the IPCC asserts, perhaps even strong enough to counter the threat of greenhouse gas-induced global warming.
- Dimethylsulfide, or DMS, is an organosulfur compound with the formula $(\text{CH}_3)_2\text{S}$. It is the most abundant biologically produced sulfur compound in the atmosphere, emitted to the air primarily by marine phytoplankton.
- Charlson *et al.* (1987) discussed the plausibility of a multistage negative feedback process whereby warming-induced increases in the emission of DMS from the world's oceans tend to counteract the effects of the initial impetus for warming. They hypothesized the global radiation balance is significantly influenced by the albedo of marine stratus clouds: the greater the cloud albedo, the less the input of solar radiation to Earth's surface. The albedo of these clouds, in turn, is known to be a function of cloud droplet concentration—the more and smaller the cloud droplets, the greater the cloud albedo and the reflection of solar radiation—which is dependent upon the availability of cloud condensation nuclei on which the droplets form: the more cloud condensation nuclei, the more and smaller the cloud droplets. In completing the negative feedback loop, Charlson *et al.* note the concentration of cloud condensation nuclei often depends upon the flux of biologically produced DMS from the world's oceans: the higher the sea surface temperature, the greater the sea-to-air flux of DMS.
- Since the publication of Charlson *et al.*'s initial work, much empirical evidence has been gathered in support of their hypothesis. The review of Ayers and Gillett (2000), for example, concludes “major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis” and there is “compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere.”
- Simo and Pedros-Alio (1999) used satellite imagery and *in situ* experiments to study the production of DMS by enzymatic cleavage of dimethylsulphoniopropionate in the North Atlantic Ocean about 400 km south of Iceland. They found the depth of the surface mixing-layer has a substantial influence on DMS yield in the short term, as do seasonal variations in vertical mixing in the longer term, which led them to conclude “climate-controlled mixing controls DMS production over vast regions of the ocean.”
- Hopke *et al.* (1999) analyzed weekly concentrations of 24 different airborne particulates measured at the northernmost manned site in the world—Alert, Northwest Territories, Canada—from 1980 to 1991. They found concentrations of biogenic sulfur, including sulfate and methane sulfonate, were low in winter but high in summer, and the year-to-year variability in the strength of the biogenic sulfur signal was strongly correlated with the mean temperature of the Northern Hemisphere. “This result,” the authors state, “suggests that as the temperature rises, there is increased biogenic production of the reduced sulfur precursor compounds that are oxidized in the atmosphere to sulfate and methane sulfonate and could be evidence of a negative feedback mechanism in the global climate system.”
- Is that negative feedback phenomenon powerful enough to counter the threat of greenhouse gas-

induced global warming? Sciare *et al.* (2000) examined ten years of DMS data from Amsterdam Island in the southern Indian Ocean, finding a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50 percent. This finding suggests the degree of warming typically predicted to accompany a doubling of the air's CO₂ content would increase the atmosphere's DMS concentration by a factor of three or more, providing what they call a "very important" negative feedback that could potentially offset the original impetus for warming.

Kouvarakis and Mihalopoulos (2002) conducted research even more directly supportive of Charlson *et al.*'s hypothesis, measuring seasonal variations of gaseous DMS and its oxidation products—non-sea-salt sulfate (nss-SO₄²⁻) and methanesulfonic acid (MSA)—at a remote coastal location in the Eastern Mediterranean Sea from May 1997 through October 1999, as well as the diurnal variation of DMS during two intensive measurement campaigns conducted in September 1997. In the seasonal investigation, measured DMS concentrations tracked sea surface temperature (SST) almost perfectly, going from a low of 0.87 nmol m⁻³ in the winter to a high of 3.74 nmol m⁻³ in the summer. The diurnal studies reached a similar conclusion: DMS concentrations were lowest when it was coldest (just before sunrise), rose rapidly as it warmed thereafter to about 1,100, after which they dipped slightly and then experienced a further rise to the time of maximum temperature at 2,000, whereupon a decline in both temperature and DMS concentration set in that continued until just before sunrise. Because concentrations of DMS and its oxidation products rise dramatically in response to both diurnal and seasonal increases in SST, there is every reason to believe the same negative feedback phenomenon would operate in the case of the long-term warming that could arise from increasing greenhouse gas concentrations, substantially muting the climatic effects of those gases.

Baboukas *et al.* (2002) report the results of nine years of measurements of methanesulfonate (MS-), an exclusive oxidation product of DMS, in rainwater at Amsterdam Island. Their data, too, revealed "a well distinguished seasonal variation with higher values in summer, in line with the seasonal variation of its gaseous precursor (DMS)," which "further confirms the findings of Sciare *et al.* (2000)." The MS-anomalies in the rainwater were found to be closely related to SST anomalies; Baboukas *et al.* say this

observation provides even more support for "the existence of a positive ocean-atmosphere feedback on the biogenic sulfur cycle above the Austral Ocean," which water body they describe as "one of the most important DMS sources of the world."

Toole and Siegel (2004) note the DMS negative feedback process has been shown to operate in the 15 percent of the world's oceans "consisting primarily of high latitude, continental shelf, and equatorial upwelling regions," where DMS may be accurately predicted as a function of the ratio of the amount of surface chlorophyll derived from satellite observations to the depth of the climatological mixed layer, which they refer to as the "bloom-forced regime." For the other 85 percent of the world's marine waters, they demonstrate modeled surface DMS concentrations are independent of chlorophyll and are a function of the mixed layer depth alone, which they called the "stress-forced regime." Their study revealed how the warming-induced DMS negative feedback cycle operates in these waters.

For oligotrophic regimes, Toole and Siegel found "DMS biological production rates are negatively or insignificantly correlated with phytoplankton and bacterial indices for abundance and productivity while more than 82% of the variability is explained by UVR(325) [ultraviolet radiation at 325 nm]." This relationship, in their words, is "consistent with recent laboratory results (e.g., Sunda *et al.*, 2002)," which demonstrated intracellular DMS concentration and its biological precursors (particulate and dissolved dimethylsulfoniopropionate) "dramatically increase under conditions of acute oxidative stress such as exposure to high levels of UVR," which "are a function of mixed layer depth."

These results—which Toole and Siegel confirmed via an analysis of the Dacey *et al.* (1998) 1992–1994 organic sulfur time-series sampled in concert with the U.S. JGOFS Bermuda Atlantic Time-Series Study (Steinberg *et al.*, 2001)—suggest, in their words, "the potential of a global change-DMS-climate feedback." Specifically, they state "UVR doses will increase as a result of observed decreases in stratospheric ozone and the shoaling of ocean mixed layers as a result of global warming (e.g., Boyd and Doney, 2002)," and "in response, open-ocean phytoplankton communities should increase their DMS production and ventilation to the atmosphere, increasing cloud condensing nuclei, and potentially playing out a coupled global change-DMS-climate feedback."

This second DMS-induced negative feedback

cycle, which operates over 85 percent of the world's marine waters and complements the first DMS-induced negative feedback cycle, which operates over the other 15 percent, is another manifestation of the capacity of Earth's biosphere to regulate its affairs in such a way as to maintain climatic conditions over the vast majority of the planet's surface.

A DMS-induced negative climate feedback phenomenon may also operate over the terrestrial surface of the globe, where the volatilization of reduced sulfur gases from soils may be just as important as marine DMS emissions in enhancing cloud albedo (Idso, 1990). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, for example, and noting additions of organic matter to a soil tend to increase the amount of sulfur gases emitted from it, Idso (1990) hypothesized that because atmospheric CO₂ is an effective aerial fertilizer, augmenting its atmospheric concentration and thereby increasing vegetative inputs of organic matter to Earth's soils should produce an impetus for cooling, even in the absence of surface warming.

About the same time Charlson *et al.* (1987) developed their hypothesis, Martin and Fitzwater (1988) and Martin *et al.* (1988) developed what has come to be known as the Iron Hypothesis (Martin, 1990), which posits that iron-rich dust swept up from exposed continental shelves during glacial maxima by the greatly enhanced winds of those periods fertilized the world's oceans to the point where their phytoplanktonic productivity rose so high it drew the air's CO₂ concentration down from typical interglacial values (280 ppm) to the much lower values characteristic of glacials (180 ppm). The IronEx studies of Martin *et al.* (1994) and Coale *et al.* (1996) confirmed the fundamental premise of this hypothesis. After fertilizing patches of seawater in high-nitrate low-chlorophyll (HNLC) regions of the equatorial Pacific with bio-available iron, they found, in the words of Turner *et al.* (2004), that this procedure "benefited all the major groups of the algal community, including those which produce significant amounts of intracellular dimethylsulfoniopropionate (DMSPp)," the precursor of DMS, which also increased in concentration as a result of the experimental iron treatment (Turner *et al.*, 1996).

In the aftermath of these demonstrations, large-scale ocean fertilization with bio-available iron came to be viewed as a viable potential strategy for the mitigation of global warming. Not only could its

implementation result in the quick removal of CO₂ from the atmosphere in response to heightened phytoplanktonic productivity, it could also lead to the reflection of more incoming solar radiation back to space as a result of greater DMSPp production.

But the studies supporting the second of these two pathways to planetary cooling had been conducted in the equatorial Pacific; it was not known whether the findings could be extrapolated to other HNLC ecosystems, such as those of the Southern Ocean. Thus, Turner *et al.* (2004) conducted two additional iron-release experiments: the Southern Ocean Iron Release Experiment (SOIREE), which took place south of Australia in February 1999, and EisenEx, which took place south of Africa in November 2000.

In both of these studies, Turner *et al.* reported "the experimental patches (~50 km²) were created by pumping dissolved iron sulfate into the mixed layer, as the ships sailed on a spiral track out from, and relative to, a buoy." The initial levels of dissolved iron in these patches rapidly decreased and additional injections were made during the experiments. "In SOIREE," the scientists note, "the major increase in DMS occurred several days after the maximum in DMSPp and by the end of the study DMS levels at 30 m depth were 6.5-fold higher in treated waters than outside," while "in EisenEx, highest observed DMS concentrations [occurred] on days 5 and 12, about 2-fold higher than initial levels." They also report a series of ocean color images from SeaWiFS revealed a feature with enhanced chlorophyll levels close to the SOIREE site (Boyd *et al.*, 2000), noting "Abraham *et al.* (2000) argue that this was our patch which had spread to cover 1100 km²."

Turner *et al.* report "recent coupled ocean-atmosphere modeling studies show that even a relatively small change in marine DMS emissions may have a significant impact on global temperatures: $\pm \sim 1^\circ\text{C}$ for a halving or doubling of DMS emissions, respectively." In addition, they note "evidence from ice cores suggests that changes in DMS emission at least as large as this have occurred in the past (Legrand *et al.*, 1991) and so it is easily conceivable that significant changes in DMS emissions would occur in future climate scenarios."

Operating in tandem, it is clear the marine-productivity-mediated increase in reflected solar radiation to space (via the Charlson *et al.* mechanism) and the more direct marine-productivity-mediated increase in the removal of CO₂ from the atmosphere possess the capacity to substantially counter whatever warming of the planet might occur in response to

future anthropogenic CO₂ emissions.

In another study of the Charlson *et al.* (1987) hypothesis, Broadbent and Jones (2004) explored the possibility that coral reefs may be major participants in the biostabilization of Earth's climate. Working in waters off the coast of Australia, they note "Jones *et al.* (1994) and Broadbent *et al.* (2002) report that corals in the Great Barrier Reef (GBR) contain significant amounts of DMSP in their zooxanthellae, suggesting that coral reefs are potentially significant sources of DMS to the water column of reef areas and that coral reefs themselves may be significant sources of atmospheric DMS to the marine boundary layer (Jones and Trevena, 2005)." The two researchers measured concentrations of DMS and DMSP within mucus ropes, coral mucus, surface films, and sediment pore waters collected from Kelso Reef, One Tree Reef, and Nelly Bay Reef in Australia's GBR. Broadbent and Jones found "the concentrations of DMS and DMSP measured in mucus ropes and surface-water samples at One Tree Reef and Kelso Reef are the highest yet reported in the marine environment," exceeding those measured in "highly productive polar waters (Fogelqvist, 1991; Trevena *et al.*, 2000, 2003), and sea ice algal communities (Kirst *et al.*, 1991; Levasseur *et al.*, 1994; Trevena *et al.*, 2003)." They state, "concentrations of DMS ranged from 61 to 18,665 nM and for DMSP, from 1,978 to 54,381 nM, representing concentration factors (CF = concentration in the mucus ropes divided by the concentration in seawater from 0.5 m depth) ranging from 59 to 12,342 for DMS and 190 to 6,926 for DMSP." In addition, they report "concentrations of DMSP in coral mucus were also exceptionally high, with mucus from *Acropora formosa* containing the highest levels of DMSP." Finally, they observe DMS and DMSP concentrations were substantially higher than water-column concentrations in both surface microlayer samples and coral-reef sediment pore waters. Broadbent and Jones conclude "the elevated concentrations of DMS and DMSP in mucus ropes, coral mucus, surface films and sediment pore waters strongly suggest that coral reefs in the GBR are significant sources of these two sulphur substances," which in turn suggests coral reefs may figure prominently in the Charlson *et al.* phenomenon that helps to keep Earth's temperature from rising too high.

Jones and Trevena (2005) measured dissolved DMS, DMSP, the water-to-air flux of DMS, and atmospheric DMS concentration during a winter

voyage through the northern GBR, Coral Sea, Gulf of Papua (GOP), and Solomon and Bismarck Seas. This work revealed the "highest levels of most of these constituents occurred in the northern GBR, NW Coral Sea and GOP, with highest levels of atmospheric DMS often occurring in south-easterly to southerly trade winds sampled in the region where the highest biomass of coral reefs occur." They also found the increase in atmospheric DMS "was mainly a result of a combination of high winds and the extremely low tides in July, when a high biomass of coral reefs in this region was aurally exposed." These findings helped solidify the link between coral zooxanthellae activity and the atmospheric concentration of DMS, which Broadbent and Jones (2004) called "a negative greenhouse gas"; i.e., one that tends to cool the planet. Thus, it broadens the base of the CLAW hypothesis (named for the four scientists of Charlson *et al.* (1987) who formulated it—Charlson, Lovelock, Andreae, and Warren) and makes it more likely the hypothesis represents a viable mechanism for tempering, and possibly even capping, global warming.

Several additional studies have probed the robustness of the CLAW hypothesis. Gunson *et al.* (2006), for example, performed a number of climate simulations using a coupled ocean-atmosphere general circulation model that included an atmospheric sulfur cycle and a marine ecosystem model. They determined "the modeled global climate is sensitive to ocean DMS production in the manner hypothesized by CLAW" and "perturbations to ocean DMS production cause significant impacts on global climate." For a halving of oceanic DMS emissions, for example, they found the modeled net cloud radiative forcing increased by 3 W/m² and, through a readjustment of the global radiative energy balance, the surface air temperature rose by 1.6°C. For a doubling of oceanic DMS emissions, they found net cloud radiative forcing declined by just under 2 W/m² and the surface air temperature decreased by just under 1°C. These findings suggest Earth's climate system is indeed capable of successfully buffering itself against the propensity for warming created by rising atmospheric CO₂ concentrations.

Wong *et al.* (2006) recorded DMS concentrations and physical oceanographic data at ocean stations P20 and P26 in the Gulf of Alaska in the Northeast Pacific Ocean. As the sea surface temperature of a region rises, they found, "the stratification of the upper water column intensifies and oceanic upwelling weakens,"

such that “in the nutrient-rich waters of the sub-Arctic Pacific, higher stratification and shallower mixed layer favor the growth of small-sized phytoplankton such as flagellates, dinoflagellates and coccolithophorids.” Noting “most prolific DMSP producers are members of these phytoplankton groups,” they state, “consequently, the local ecosystem is shifted towards one with structure and function adapted to production of DMSP and DMS.”

The four researchers point out, “globally, a larger part of the warming oceans may have highly stratified water for a longer part of the year,” adding “these conditions could enhance the shift in the marine ecosystem described herein, and might induce more rapid turnover of DMSP and higher production of DMS,” such that “in a warming global climate, we might anticipate an increasing emission of biogenic DMS from the ocean surface,” which would tend to counteract whatever impetus for warming was causing sea surface temperatures to rise.

Also in 2006, Meskhidze and Nenes explored the effects of ocean biological productivity on the microphysical and radiative properties of marine clouds over a large and seasonally recurring phytoplankton bloom in the Southern Ocean in the vicinity of South Georgia Island, where upwelling nutrient-rich waters “can support massive phytoplankton blooms, with chlorophyll *a* concentrations more than an order of magnitude higher than the background.” They used the Sea-viewing Wide Field-of-view Sensor to obtain the needed chlorophyll data and the Moderate Resolution Imaging Spectroradiometer to determine the effective radii of cloud condensation nuclei.

The researchers discovered “cloud droplet number concentration over the bloom was twice what it was away from the bloom, and cloud effective radius was reduced by 30%,” such that “the resulting change in the short-wave radiative flux at the top of the atmosphere was -15 watts per square meter, comparable to the aerosol indirect effect over highly polluted regions.” Meskhidze and Nenes conclude secondary organic aerosol formation in remote marine air may need to be included in global climate models, as it may play, as they describe it, “a considerable role in climate transition.”

In another experiment, part of the Third Pelagic Ecosystem CO₂ Enrichment Study, Wingenter *et al.* (2007) investigated the effects of atmospheric CO₂ enrichment on marine microorganisms within nine marine mesocosms maintained within 2-m-diameter polyethylene bags submerged to a depth of 10 m in a

fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espesgrend, Norway. Three of these mesocosms were maintained at ambient levels of CO₂ (~375 ppm or base CO₂), three were maintained at levels expected to prevail at the end of the current century (760 ppm or 2xCO₂), and three were maintained at levels predicted for the middle of the next century (1150 ppm or 3xCO₂). During the 25 days of their experiment, the 12 researchers followed the development and subsequent decline of induced blooms of the coccolithophorid *Emiliania huxleyi* in the three CO₂ environments, carefully measuring several physical, chemical, and biological parameters along the way.

Wingenter *et al.*'s measurements and analyses indicated “dimethylsulfide production followed the development and decline of the phytoplankton bloom” and “maximum DMS concentrations coincided with the peak in chlorophyll-*a* concentrations in the present day CO₂ treatment, but were delayed by 1–3 days relative to chlorophyll-*a* in the double and triple CO₂ treatments.” In addition, they found “DMS was 26% and 18% higher in the 2x and 3xCO₂ mesocosms, respectively (days 0–17).” The iodocarbon chloriodomethane (CH₂CI) had its peak concentration about 6 to 10 days after the chlorophyll-*a* maximum, but its estimated abundance was 46 percent higher in the 2xCO₂ mesocosms and 131 percent higher in the 3xCO₂ mesocosms.

The international team of scientists concludes “the differences in DMS and CH₂CI concentrations may be viewed as a result of changes to the ecosystems as a whole brought on by the CO₂ perturbations.” Because emissions of both DMS (Bates *et al.*, 1992) and various iodocarbons (O'Dowd *et al.*, 2002; Jimenez *et al.*, 2003) typically lead to an enhancement of cloud condensation nuclei in the marine atmosphere, the CO₂-induced stimulations of the marine emissions of these two substances provide a natural brake on the tendency for global warming to occur, as they lead to the creation of more highly reflective clouds over greater areas of the world's oceans. Consequently, as Wingenter *et al.* note, “these processes may help contribute to the homeostasis of the planet.”

Vogt *et al.* (2008) also analyzed the effects of atmospheric CO₂ enrichment on marine microorganisms and DMS production under the same three CO₂ concentrations as those employed by Wingenter *et al.* (2007)—375, 760, and 1150 ppm—for a period of 24 days. They found no significant phytoplankton species shifts among treatments and

noted “ecosystem composition, bacterial and phytoplankton abundances and productivity, grazing rates and total grazer abundance and reproduction were not significantly affected by CO₂-induced effects,” citing in support of this statement the work of Riebesell *et al.* (2007), Riebesell *et al.* (2008), Egge *et al.* (2007), Paulino *et al.* (2007), Larsen *et al.* (2007), Suffrian *et al.* (2008), and Carotenuto *et al.* (2007). In addition, they note “while DMS stayed elevated in the treatments with elevated CO₂, we observed a steep decline in DMS concentration in the treatment with low CO₂” i.e., the ambient CO₂ treatment.

The eight researchers conclude “the system under study was surprisingly resilient to abrupt and large pH changes,” contrary to what the IPCC characteristically predicts about CO₂-induced “ocean acidification.” That may be why Vogt *et al.* describe the marine ecosystem they studied as “surprisingly” resilient.

Working in the coastal waters of Korea from November 21 to December 11, 2008, Kim *et al.* (2010) also conducted a CO₂ enrichment experiment, utilizing 2,400-liter mesocosm enclosures to simulate three sets of environmental conditions—an ambient control (~400 ppm CO₂ and ambient temperature), an acidification treatment (~900 ppm CO₂ and ambient temperature), and a greenhouse treatment (~900 ppm CO₂ and ~3°C warmer-than-ambient temperature). Within these mesocosms they initiated phytoplankton blooms by adding equal quantities of nutrients to each mesocosm on day 0, while for 20 days thereafter they measured numerous pertinent parameters within each mesocosm. They found “the total accumulated DMS concentrations (integrated over the experimental period) in the acidification and greenhouse mesocosms were approximately 80% and 60% higher than the values measured in the control mesocosms, respectively.”

“Autotrophic nanoflagellates (which are known to be significant DMSP producers) showed increased growth in response to elevated CO₂,” they note, and “grazing rates [of microzooplankton] were significantly higher in the treatment mesocosms than in the control mesocosms.” Kim *et al.* conclude, “in the context of global environmental change, the key implication of our results is that DMS production resulting from CO₂-induced grazing activity may increase under future high CO₂ conditions” and, therefore, “DMS production in the ocean may act to counter the effects of global warming in the future.”

Watanabe *et al.* (2007) utilized sea surface DMS

data and other hydrographic parameters measured in the North Pacific Ocean between latitudes 25 and 55°N to develop and validate an empirical equation for sea surface DMS concentration that uses sea surface temperature, sea surface nitrate concentration, and latitude as input data. By applying the algorithm they developed to hydrographic time series data sets pertaining to the western North Pacific that span the period 1971 to 2000, the seven researchers found the annual flux of DMS from sea to air in that region increased by 1.9–4.8 μmol m⁻² year⁻¹. This increase, they write, “was equal to the annual rate of increase of about 1% of the climatological annual averaged flux of DMS in the western North Pacific in the last three decades.” These observations suggest the negative climate feedback phenomenon driven by increasing oceanic DMS concentrations is “alive and well.”

Working with climate and DMS production data from the region of the Barents Sea (70–80°N, 30–35°E) obtained over the period 1998 to 2002, Qu and Gabric (2010) employed a genetic algorithm to calibrate chlorophyll-*a* measurements (obtained from SeaWiFS satellite data) for use in a regional DMS production model. Then, using GCM temperature outputs for the periods of 1960–1970 (pre-industry CO₂ level) and 2078–2086 (triple the pre-industry CO₂ level), they calculated the warming-induced enhancement of the DMS flux from the Barents Sea region. The two researchers report “significantly decreasing ice coverage, increasing sea surface temperature and decreasing mixed-layer depth could lead to annual DMS flux increases of more than 100% by the time of equivalent CO₂ tripling (the year 2080).” They state “such a large change would have a great impact on the Arctic energy budget and may offset the effects of anthropogenic warming that are amplified at polar latitudes” and add “many of these physical changes will also promote similar perturbations for other biogenic species (Leck *et al.*, 2004), some of which are now thought to be equally influential to the aerosol climate of the Arctic Ocean.”

One year later, working with *Phaeocystis antarctica*—a polar prymnesiophyte or haptophyte (marine microalga or phytoplankton)—Orellana *et al.* (2011) measured the concentrations of DMS and DMSP in whole cells and isolated secretory vesicles of the species as well as in samples of broken cells, because, as they elucidated, “in addition to autolysis (Hill *et al.*, 1998), viral lysis (Malin *et al.*, 1998), and zooplankton grazing (Dacey and Wakeham, 1986;

Wolfe and Steinke, 1996), it is believed that DMSP passively diffuses into seawater.” They note “understanding the regulation of this mechanism is necessary in order to obtain a correct partitioning of the cellular and extracellular DMSP and DMS pools in seawater and allow predictions of global budgets.” The four U.S. researchers demonstrate “DMSP and DMS were stored in the secretory vesicles of *Phaeocystis antarctica*,” where “they were trapped within a polyanionic gel matrix, which prevented an accurate measurement of their concentration in the absence of a chelating agent.” They conclude, “the pool of total DMSP in the presence of *Phaeocystis* may be underestimated by as much as half.”

Noting “models for the distribution of marine DMS have lately been increasing in number and complexity, such that a regional portrait of their evolving climate response is constructible,” Cameron-Smith *et al.* (2011) employed the most recent version of the Community Climate System Model (CCSM), described by Collins *et al.* (2006), to produce the first marine sulfur simulations performed with what they refer to as “the most sophisticated ocean sulfur cycle model yet reported.”

In one of their simulations, the atmospheric CO₂ concentration was held steady at 355 ppm, while in another it was set at 970 ppm in order to simulate the climate near the end of the twenty-first century as projected by the IPCC (2001) SRES A1F1 emissions scenario. The latter CO₂ concentration and its modeled climatic consequences resulted in the simulation of “rings of high DMS near Antarctica due to the inclusion of a *Phaeocystis* parameterization.” This unicellular, photosynthetic, eukaryotic alga generates, in the words of the five U.S. scientists, “several times the typical DMSP level (dimethyl sulfoniopropionate, a major DMS precursor) and favors cold water habitat (Matrai and Vernet, 1997).”

Consequently, the modeled global warming produced by the specified increase in the atmosphere’s CO₂ concentration resulted in a migration of *Phaeocystis* species toward the cooler waters of higher latitudes. Under these conditions the model employed by Cameron-Smith *et al.* simulated increases in the “zonal averaged DMS flux to the atmosphere of over 150% in the Southern Ocean,” which they report was “due to concurrent sea ice changes and ocean ecosystem composition shifts caused by changes in temperature, mixing, nutrient, and light regimes.” Based on other modeling exercises they conducted, they state the shift in the location of maximum DMS emissions towards colder

regions “is usually reinforced with even more sophisticated models.”

Cameron-Smith and colleagues conclude, “in global estimates involving constant upward or downward DMS flux changes, average planetary surface temperatures separate by three or more degrees Celsius,” citing the work of Charlson *et al.* (1987) and Gunson *et al.* (2006). This strong biological response to a CO₂-induced impetus for warming can result in a greatly strengthened negative regional feedback that results in more incoming solar radiation being reflected back to space with enhanced regional cooling. The resulting DMS-enhanced “thermal insulating” of Antarctica from the rest of the world by this mechanism could significantly reduce the propensity for that continent’s ice sheets to lose mass and contribute to sea level rise, even in a world that is experiencing a net warming.

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2.5.2.2 Terrestrial

Just as marine phytoplankton respond to rising temperatures by emitting gases that ultimately lead to less global warming, so too do terrestrial plants. What is more, Earth's terrestrial plants have a tendency to operate in this manner more effectively as the air's CO₂ content rises.

A good introduction to this subject is provided by the review paper of Peñuelas and Llusia (2003), who point out biogenic volatile organic compounds (BVOCs) constitute “one of nature's biodiversity treasures.” Comprised of isoprene, terpenes, alkanes, alkenes, alcohols, esters, carbonyls, and acids, this diverse group of substances is produced by a variety of processes occurring in many plant tissues. Some of the functions of these substances, according to the two scientists, include acting as “deterrents against pathogens and herbivores, or to aid wound sealing after damage (Pichersky and Gershenzon, 2002).” They also state BVOCs provide a means “to attract pollinators and herbivore predators, and to communicate with other plants and organisms (Peñuelas *et al.*, 1995; Shulaev *et al.*, 1997).”

Of particular importance within the context of global climate change, in the opinion of Peñuelas and Llusia, is the growing realization that “isoprene and monoterpenes, which constitute a major fraction of BVOCs, might confer protection against high temperatures” by acting “as scavengers of reactive oxygen species produced [within plants] under high temperatures.” The claimed ill effects of CO₂-induced global warming on Earth's vegetation thus may be countered by two ameliorative phenomena: the aerial fertilization effect of atmospheric CO₂ enrichment, which is typically more strongly expressed at higher temperatures, and the tendency for rising air temperatures and CO₂ concentrations to spur the production of higher concentrations of heat-stress-reducing BVOCs. With respect to temperature, Peñuelas and Llusia calculate “global warming over the past 30 years could have increased the BVOC global emissions by approximately 10 percent, and a

further 2–3°C rise in the mean global temperature ... could increase BVOC global emissions by an additional 30–45 percent.”

Other phenomena may similarly favor plants. Peñuelas and Llusia note “the increased release of nitrogen into the biosphere by man probably also enhances BVOC emissions by increasing the level of carbon fixation and the activity of the responsible enzymes (Litvak *et al.*, 1996).” The conversion of abandoned agricultural lands to forests and the implementation of planned reforestation projects should help the rest of the biosphere too; Peñuelas and Llusia report additional numbers of “*Populus*, *Eucalyptus* or *Pinus*, which are major emitters, might greatly increase BVOC emissions.”

With respect to how increased BVOC emissions might affect climate change itself, Peñuelas and Llusia point out “BVOCs generate large quantities of organic aerosols that could affect climate significantly by forming cloud condensation nuclei.” They conclude, “there should be a net cooling of the Earth's surface during the day because of radiation interception,” noting Shallcross and Monks (2000) “have suggested that one of the reasons plants emit the aerosol isoprene might be to cool the surroundings in addition to any physiological or evaporative effects that might cool the plant directly.”

Not all experiments have reported increases in plant BVOC emissions with increasing atmospheric CO₂ concentrations. Rapparini *et al.* (2004) found long-term exposure to high levels of atmospheric CO₂ did not significantly affect BVOC emissions from mature downy and holly oak trees growing close to a natural CO₂ spring in central Italy. Similarly, Constable *et al.* (1999) reported no effect of elevated CO₂ on monoterpene emissions from Ponderosa pine and Douglas fir trees. And some studies have reported decreases in BVOC emissions, such as those of Vuorinen *et al.* (2004), who worked with cabbage plants, and Loreto *et al.* (2001), who studied monoterpene emissions from oak seedlings. But Staudt *et al.* (2001) observed CO₂-induced increases in BVOC emissions in the identical species of oak studied by Vuorinen *et al.* (2004).

An explanation for this wide range of results comes from Baraldi *et al.* (2004), who—after exposing sections of a southern California chaparral ecosystem to atmospheric CO₂ concentrations ranging from 250 to 750 ppm in 100-ppm increments for a period of four years—concluded “BVOC emission can remain nearly constant as rising CO₂ reduces

emission per unit leaf area while stimulating biomass growth and leaf area per unit ground area.” In most of the cases investigated, however, BVOC emissions tended to increase with atmospheric CO₂ enrichment, and the increases were often large.

Jasoni *et al.* (2003), for example, grew onions from seed for 30 days in individual cylindrical flow-through growth chambers under controlled environmental conditions at atmospheric CO₂ concentrations of either 400 or 1,000 ppm. At the end of the study, the plants in the CO₂-enriched chambers had 40 percent more biomass than the plants grown in ambient air, and their photosynthetic rates were 22 percent greater. In addition, the CO₂-enriched plants exhibited 17-fold and 38-fold increases in emissions of the BVOC hydrocarbons 2-undecanone and 2-tridecanone, respectively, which Jasoni *et al.* note “confer insect resistance against a major agricultural pest, spider mites.” They conclude “plants grown under elevated CO₂ will accumulate excess carbon and at least a portion of this excess carbon is funneled into an increased production of BVOCs.”

Focusing on actively wet-spore-discharging Ascomycota (AAM) and actively wet-spore-discharging Basidiomycota (ABM), Elbert *et al.* (2007) “address the active (forcible) discharge of fungal spores, which is accompanied by the emission of aqueous droplets containing carbohydrates and inorganic ions, ... summarize the information on the atmospheric abundance of wet and dry discharged fungal spores that is available from earlier scientific studies made at various locations around the world, ... and present new measurement results and budget calculations for aerosol samples from tropical rainforests in Amazonia.” The four researchers confirmed AAM and ABM are major sources of primary biogenic aerosols, finding from their own work that “in pristine tropical rainforest air, fungal spores indeed account for a major fraction of coarse particulate matter (up to ~45%).” They also calculated the emission rate of total fungal spores (~50 Tg yr⁻¹) “is of similar magnitude as current estimates of the rates of emission and formation of other types of continental air particulate matter (primary and secondary organic aerosols).”

Of particular interest in the context of rising near-surface air temperatures and atmospheric CO₂ concentrations, Elbert *et al.* write, “global warming and increasing CO₂ concentrations may enhance the spread of fungi and emission of fungal spores,” citing the works of Klironomos *et al.* (1997), Hoyer *et al.* (2007), and Raupach *et al.* (2007), while further

concluding “an increase of fungal spores acting as cloud condensation and ice nuclei may influence the hydrological cycle and provide either positive or negative feedbacks to climate change.”

Raisanen *et al.* (2008) sought to determine to what extent a doubling of the air’s CO₂ content and a 2°–6°C increase in air temperature might affect the emission of monoterpenes from 20-year-old Scots pine (*Pinus sylvestris* L.) seedlings. They studied the two phenomena and their interaction within closed-top chambers built on a naturally seeded stand of the trees in eastern Finland that had been exposed to the four treatments—ambient CO₂ and ambient temperature, ambient temperature and elevated CO₂, ambient CO₂ and elevated temperature, elevated temperature and elevated CO₂—for the prior five years.

Over the five-month growing season of May–September, the three Finnish researchers found total monoterpene emissions in the elevated-CO₂-only treatment were 5 percent greater than those in the ambient CO₂, ambient temperature treatment. Emissions in the elevated-temperature-only treatment were 9 percent less than those in ambient air. In the presence of both elevated CO₂ and elevated temperature, there was an increase of fully 126 percent in the total amount of monoterpenes emitted over the growing season, which led the authors to conclude, “the amount of monoterpenes released by Scots pines into the atmosphere during a growing season will increase substantially in the predicted future climate.”

Kavouras *et al.* (1998) measured a number of atmospheric gases and particles in a eucalyptus forest in Portugal and analyzed their observations for evidence of biologically produced gases being converted to particles that could function as cloud condensation nuclei. They found certain hydrocarbons emitted by vegetation (isoprene and terpenes, in particular) do indeed experience gas-to-particle transformations. Aerosols (or *biosols*) produced from two of these organic acids (cis- and trans-pinonic acid) comprised as much as 40 percent of the fine particle atmospheric mass during daytime hours.

A similar study was conducted by O’Dowd *et al.* (2002), who measured aerosol electrical-mobility size-distributions before and during the initial stage of an atmospheric nucleation event over a boreal forest in Finland. Simultaneously, organic vapor growth rate measurements were made of particles that nucleated into organic cloud-droplets in the flow-tube cloud

chamber of a modified condensation-particle counter. They determined newly formed aerosol particles over forested areas “are composed primarily of organic species, such as cis-pinonic acid and pinonic acid, produced by oxidation of terpenes in organic vapors released from the canopy.” They point out “aerosol particles produced over forested areas may affect climate by acting as nuclei for cloud condensation,” adding there remain numerous uncertainties involving complex feedback processes “that must be determined if we are to predict future changes in global climate.”

Also working in Finland, Tunved *et al.* (2006) analyzed a five-year (1999–2004) April–September database of aerosol number-size distribution obtained from three monitoring stations in the Finnish boreal zone of Europe—Varrio (67°46'N, 29°35'E), Pallas (68°01'N, 24°10'E), and Hyytiälä (61°51'N, 24°17'E)—in an investigation of “the characteristic changes of the aerosol population in air masses undergoing marine to continental transition over forested areas in northern Norway, Sweden and Finland” that are “substantially lacking in anthropogenic aerosol sources.” According to the ten European researchers authoring this study, their results “clearly show that a substantial gas-to-particle [trans]formation of biogenic volatile organic carbon [BVOC] to secondary organic aerosol [SOA] takes place over the boreal forest in northern Europe” and “these BVOCs are most likely emitted from the forest itself and, based on previous findings, are most likely constituted of terpenes.”

Their analysis further “suggests an apparent mass yield in the range of 5 to 10%” and that “the boreal forest typically sustains 1000 to 2000 particles cm^{-3} in a climatic relevant size range (~40 to 100 nm).” Because they “provided a similar mechanistic and quantitative behavior for two widely separate locations (more than 700 km apart),” they report, “the derived relations suggest that similar mechanisms control the aerosol number and mass evolution over large areas in the boreal regions of the Northern Hemisphere.” Tunved *et al.* conclude their findings have “important implications for radiation budget estimates and relevancy for the evaluation of feedback loops believed to determine our future climate,” noting their study establishes that boreal forest “is a major source of climate-relevant aerosol particles” “capable of competing with the anthropogenic CCN [cloud condensation nuclei] loadings transported over forested areas.”

Shifting from trees to a much smaller plant, Kuhn

and Kesselmeier (2000) collected lichens from an open oak woodland in central California, USA and studied their uptake of carbonyl sulfide (COS) in a dynamic cuvette system under controlled conditions in the laboratory. When the lichens were optimally hydrated, COS was absorbed from the atmosphere by the lichens at a rate that gradually doubled as air temperature rose from approximately 3° to 25°C, whereupon the rate of COS absorption dropped precipitously, reaching a value of zero at 35°C.

COS is the most stable and abundant reduced sulfur gas in the atmosphere and a major player in determining Earth’s radiation budget. After making its way into the stratosphere, it can be photo-dissociated, as well as oxidized, to form SO_2 , which is typically converted to sulfate aerosol particles that are highly reflective of incoming solar radiation and, therefore, have the capacity to significantly cool Earth as more and more of them collect above the tropopause. Biologically modulated COS concentrations may play a role in regulating Earth’s surface air temperature.

Once air temperature rises above 25°C, the rate of removal of COS from the air by this species of lichen declines dramatically. More COS thus remains in the air and is likely to make its way into the stratosphere, where it can be converted into sulfate aerosol particles that can reflect more incoming solar radiation back to space and thereby cool Earth. Since the consumption of COS by lichens is under the physiological control of carbonic anhydrase, which is the key enzyme for COS uptake in all higher plants, algae, and soil organisms, this phenomenon is likely to be generally operative throughout much of the plant kingdom. This biological “thermostat” may be powerful enough to define an upper limit above which the surface air temperature of the planet may be restricted from rising, even when changes in other forcing factors, such as greenhouse gases, produce an impetus for it to do so. (For more about COS, see Section 2.6.2 below.)

Although BVOCs emitted from terrestrial plants both small and large are important to Earth’s climate, trees tend to dominate. Recent research suggests another way in which their response to atmospheric CO_2 enrichment may provide an effective counterbalance to the greenhouse properties of CO_2 .

The phenomenon begins with the propensity for CO_2 -induced increases in BVOCs, together with the cloud particles they spawn, to enhance the amount of diffuse solar radiation reaching Earth’s surface

(Suraqui *et al.*, 1974; Abakumova *et al.*, 1996). That is followed by the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies (Roderick *et al.*, 2001), followed by the tendency for less internal canopy shading to enhance whole-canopy photosynthesis (Healey *et al.*, 1998). The end result is a greater photosynthetic extraction of CO₂ from the air and subsequent reduction of the strength of the atmosphere's greenhouse effect.

The significance of this process is described and documented at some length in Section 2.6.3 of this report. For example, Roderick *et al.* conclude the Mt. Pinatubo eruption—a unique natural experiment to evaluate the overall climatic sensitivity of the planet—may have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial photosynthesis in the year following the eruption. Additional real-world evidence for the existence of this phenomenon was provided by Gu *et al.* (2003), Law *et al.* (2002), Farquhar and Roderick (2003), Reichenau and Esser (2003), and Niyogi *et al.* (2004).

One final beneficial effect of CO₂-induced increases in BVOC emissions is the propensity of BVOCs to destroy tropospheric ozone, as documented by Goldstein *et al.* (2004). Earth's vegetation is responsible for the production of vast amounts of ozone (O₃) (Chameides *et al.*, 1988; Harley *et al.*, 1999), but it is also responsible for destroying much of it. Goldstein *et al.* mention three major routes by which O₃ exits the air near Earth's surface: leaf stomatal uptake, surface deposition, and within-canopy gas-phase chemical reactions with BVOCs.

The first of these exit routes, according to Goldstein *et al.*, accounts for 30 to 90 percent of total ecosystem O₃ uptake from the atmosphere (that is, O₃ destruction), and the remainder typically has been attributed to deposition on non-stomatal surfaces. However, they note “Kurpius and Goldstein (2003) recently showed that the non-stomatal flux increased exponentially as a function of temperature at a coniferous forest site,” and “the exponential increase with temperature was consistent with the temperature dependence of monoterpene emissions from the same ecosystem, suggesting O₃ was lost via gas phase reactions with biogenically emitted terpenes before they could escape the forest canopy.”

Schade and Goldstein (2003) had demonstrated forest thinning dramatically enhances monoterpene emissions. Goldstein *et al.* (2004) took another important step toward clarifying the issue by measuring the effect of forest thinning on O₃

destruction in an attempt to see if it is enhanced along with the thinning-induced increase in monoterpene emissions.

In a ponderosa pine plantation in the Sierra Nevada Mountains of California, USA, a management procedure to improve forest health and optimize tree growth was initiated on May 11, 2000 and continued through June 15, 2000. This procedure involved the use of a masticator to mechanically “chew up” smaller unwanted trees and leave their debris on site, which reduced plantation green leaf biomass by just over half. Monoterpene mixing ratios and fluxes were measured hourly within the plantation canopy, while total ecosystem O₃ destruction was “partitioned to differentiate loss due to gas-phase chemistry from stomatal uptake and deposition.”

Goldstein *et al.* report both the destruction of ozone due to gas-phase chemistry and emissions of monoterpenes increased dramatically with the onset of thinning, and these phenomena continued in phase with each other thereafter. They “infer that the massive increase of O₃ flux during and following mastication is driven by loss of O₃ through chemical reactions with unmeasured terpenes or closely related BVOCs whose emissions were enhanced due to wounding [by the masticator].” They write, “considered together, these observations provide a conclusive picture that the chemical loss of O₃ is due to reactions with BVOCs emitted in a similar manner as terpenes” and “we can conceive no other possible explanation for this behavior other than chemical O₃ destruction in and above the forest canopy by reactions with BVOCs.”

Goldstein *et al.* conclude their results “suggest that total reactive terpene emissions might be roughly a factor of 10 higher than the typically measured and modeled monoterpene emissions, making them larger than isoprene emissions on a global scale.” This would mean vegetative emissions of terpenes, which lead to the destruction of ozone, are significantly greater than vegetative emissions of isoprene, which lead to the creation of ozone (Poisson *et al.*, 2000). In addition, there is substantial evidence to suggest the ongoing rise in the air's CO₂ content may lead to an overall reduction in vegetative isoprene emissions while enhancing vegetative productivity, which may lead to an overall increase in vegetative terpene emissions. There is thus reason to believe the ongoing rise in the air's CO₂ content will help reduce the ongoing rise in the air's O₃ concentration.

There is growing evidence that rising air

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temperatures and atmospheric CO₂ concentrations significantly increase desirable vegetative BVOC emissions, particularly from trees—the most prominent photosynthetic force on the planet—and that this phenomenon has important and highly beneficial biospheric consequences. These findings further demonstrate that the biology of Earth influences the climate of Earth. They reveal a direct connection between the metabolic activity of trees and the propensity for the atmosphere to produce clouds; the metabolic activity of lichens and the presence of sulfate aerosol particles in the atmosphere that reflect incoming solar radiation; and the increased presence of BVOCs caused by rising CO₂ and an increase in diffuse solar radiation, which leads to increased photosynthetic extraction of CO₂ from the air. In each case, the relationship is self-protecting of the biosphere, and in each case the feedbacks are either ignored or downplayed by the IPCC.

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2.5.2.2.1 Isoprene

Isoprene (C₅H₈ or 2-methyl-1,3-butadiene) is a highly reactive non-methane hydrocarbon (NMHC) emitted by vegetation; it is responsible for the production of tropospheric ozone (Chameides *et al.*, 1988; Harley *et al.*, 1999), a debilitating scourge of plant and animal life alike. Poisson *et al.* (2000) calculated current levels of NMHC emissions—the vast majority of which are isoprene, accounting for more than twice as much as all other NMHCs combined—may increase surface ozone concentrations by up to 40 percent in the marine boundary-layer and 50 to 60 percent over land. They further estimated the current tropospheric ozone content extends the atmospheric lifetime of methane, one of the world's most powerful greenhouse gases, by approximately 14 percent.

A few experiments have suggested elevated concentrations of atmospheric carbon dioxide have little or no effect on the emission of isoprene by certain plant species (Buckley, 2001; Baraldi *et al.*, 2004; Rapparini *et al.*, 2004). But a much larger number of experiments suggest substantial CO₂-induced reductions in isoprene emissions, as demonstrated by the work of Monson and Fall (1989), Loreto and Sharkey (1990), Sharkey *et al.* (1991), and Loreto *et al.* (2001). We here provide short synopses of several other such studies along with some of the implications of their more robust findings.

Rosentiel *et al.* (2003) studied three 50-tree cottonwood plantations growing in separate mesocosms within the forestry section of the Biosphere 2 facility near Oracle, Arizona, USA. One of these mesocosms was maintained at an

atmospheric CO₂ concentration of 430 ppm, while the other two were enriched to concentrations of 800 and 1,200 ppm for an entire growing season. Integrated over that period, the total above-ground biomass of the trees in the latter two mesocosms was increased by 60 percent and 82 percent, respectively, while their production of isoprene was decreased by 21 percent and 41 percent, respectively.

Scholefield *et al.* (2004) measured isoprene emissions from *Phragmites australis* (a grass) growing at different distances from a natural CO₂ spring in central Italy. Atmospheric CO₂ concentrations of approximately 350, 400, 550, and 800 ppm had likely prevailed at the locations they measured for the entire lifetimes of the plants. Across this CO₂ gradient, plant isoprene emissions fell as the air's CO₂ concentration rose. Over the first 50 ppm CO₂ increase, isoprene emissions were reduced to approximately 65 percent of what they were at ambient CO₂; for CO₂ increases of 200 and 450 ppm, isoprene emissions were reduced to about 30 percent and 7 percent of what they were in the 350-ppm-CO₂ air. The researchers note these reductions were likely caused by reductions in leaf isoprene synthase, which was observed to be highly correlated with isoprene emissions. This led them to conclude, “elevated CO₂ generally inhibits the expression of isoprenoid synthesis genes and isoprene synthase activity which may, in turn, limit formation of every chloroplast-derived isoprenoid.” They thus state the “basal emission rate of isoprene is likely to be reduced under future elevated CO₂ levels.”

Centritto *et al.* (2004) grew hybrid poplar saplings for one full growing season in a forced-air CO₂ enrichment (FACE) facility located at Rapolano, Italy, where the air's CO₂ concentration was increased by approximately 200 ppm. They found “isoprene emission is reduced in elevated CO₂, in terms of both maximum values of isoprene emission rate and isoprene emission per unit of leaf area averaged across the total number of leaves per plant,” a reduction of approximately 34 percent. When isoprene emission was summed over the entire plant profile, the reduction was not nearly so great (only 6 percent), because of the greater number of leaves on the CO₂-enriched saplings. “However,” they point out, “Centritto *et al.* (1999), in a study with potted cherry seedlings grown in open-top chambers, and Gielen *et al.* (2001), in a study with poplar saplings exposed to FACE, showed that the stimulation of total leaf area in response to elevated CO₂ was a transient

effect, because it occurred only during the first year of growth.” Thus, they conclude, “it may be expected that with similar levels of leaf area, the integrated emission of isoprene would have been much lower in elevated CO₂.” They say their work, “as well as that reported by Scholefield *et al.* (2004), in a companion experiment on *Phragmites* growing in a nearby CO₂ spring, mostly confirm that isoprene emission is inversely dependent on CO₂ [concentration] when this is above ambient, and suggests that a lower fraction of C will be re-emitted in the atmosphere as isoprene by single leaves in the future.”

Working at the Aspen FACE facility near Rhinelander, Wisconsin, USA, Calfapietra *et al.* (2008) measured emissions of isoprene from sun-exposed upper-canopy leaves of an O₃-tolerant clone and an O₃-sensitive clone of trembling aspen (*Populus tremuloides* Michx.) trees growing in either normal ambient air, air enriched with an extra 190–200 ppm CO₂, air with 1.5 times the normal ozone concentration, or air simultaneously enriched with the identical concentrations of both gases.

For trees growing in air of ambient ozone concentration, the extra 190 ppm of CO₂ decreased the mean isoprene emission rate by 11.7 percent in the O₃-tolerant aspen clone and by 22.7 percent in the O₃-sensitive clone. For trees growing in air with 1.5 times the ambient ozone concentration, the extra CO₂ decreased the mean isoprene emission rate by 10.4 percent in the O₃-tolerant clone and by 32.7 percent in the O₃-sensitive clone. At the same time, and in the same order, net photosynthesis rates were increased by 34.9 percent, 47.4 percent, 31.6 percent, and 18.9 percent.

Possell *et al.* (2004) grew seedlings of English oak (*Quercus robur*), one to a mesocosm (16 cm diameter, 60 cm deep), in either fertilized or unfertilized soil in solardomes maintained at atmospheric CO₂ concentrations of either ambient or ambient plus 300 ppm for one full year, at the conclusion of which period they measured rates of isoprene emissions from the trees’ foliage together with their rates of photosynthesis. In the unfertilized trees, the 300 ppm increase in the air’s CO₂ concentration reduced isoprene emissions by 63 percent on a leaf area basis and 64 percent on a biomass basis, while in the fertilized trees the extra CO₂ reduced isoprene emissions by 70 percent on a leaf area basis and 74 percent on a biomass basis. In addition, the extra CO₂ boosted leaf photosynthesis rates by 17 percent in the unfertilized trees and 13 percent in the fertilized trees.

Possell *et al.* (2005) performed multiple three-week-long experiments with two known isoprene-emitting herbaceous species (*Mucuna pruriens* and *Arundo donax*), which they grew in controlled environment chambers maintained at two different sets of day/night temperatures (29/24°C and 24/18°C) and atmospheric CO₂ concentrations characteristic of glacial (180 ppm), preindustrial (280 ppm), and current (366 ppm) conditions, where canopy isoprene emission rates were measured on the final day of each experiment. They obtained what they describe as “the first empirical evidence for the enhancement of isoprene production, on a unit leaf area basis, by plants that grew and developed in [a] CO₂-depleted atmosphere.” These results, in their words, “support earlier findings from short-term studies with woody species (Monson and Fall, 1989; Loreto and Sharkey, 1990).”

Then, combining their emission rate data with those of Rosenstiel *et al.* (2003) for *Populus deltoides*, Centritto *et al.* (2004) for *Populus x euroamericana*, and Scholefield *et al.* (2004) for *Phragmites australis*, Possell *et al.* developed a single downward-trending isoprene emissions curve that stretches from 180 to 1,200 ppm CO₂, where it asymptotically approaches a value that is an order of magnitude less than what it is at 180 ppm.

Working at the Biosphere 2 facility near Oracle, Arizona, USA in enclosed ultraviolet light-depleted mesocosms (to minimize isoprene depletion by atmospheric oxidative reactions such as those involving OH), Pegoraro *et al.* (2005) studied the effects of atmospheric CO₂ enrichment (1,200 ppm compared to an ambient concentration of 430 ppm) and drought on the emission of isoprene from cottonwood (*Populus deltoides* Bartr.) foliage and its absorption by the underlying soil for both well-watered and drought conditions. They found “under well-watered conditions in the agriforest stands, gross isoprene production (i.e., the total production flux minus the soil uptake) was inhibited by elevated CO₂ and the highest emission fluxes of isoprene were attained in the lowest CO₂ treatment.” The elevated CO₂ treatment resulted in a 46 percent reduction in gross isoprene production. In addition, the researchers found drought suppressed the isoprene sink capacity of the soil beneath the trees, but “the full sink capacity of dry soil was recovered within a few hours upon rewetting.”

Putting a slightly negative slant on their findings, Pegoraro *et al.* suggest “in future, potentially hotter, drier environments, higher CO₂ may not mitigate

isoprene emission as much as previously suggested.” But it should be noted that climate models generally predict an intensification of the hydrologic cycle in response to rising atmospheric CO₂ concentrations, and that the anti-transpirant effect of atmospheric CO₂ enrichment typically leads to increases in the moisture contents of soils beneath vegetation. Over the latter decades of the twentieth century, when the IPCC claims Earth warmed at a rate and to a level unprecedented over the past two millennia, soil moisture data from around the world tended to display upward trends. Robock *et al.* (2000), for example, collected soil moisture data from more than 600 stations across a variety of climatic regimes, determining, “In contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen.” In a subsequent study of “45 years of gravimetrically observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April–October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958–2002,” Robock *et al.* (2005) found “a positive soil moisture trend for the entire period of observation,” noting “even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals.” A CO₂-enriched world of the future will likely present the best of both aspects of isoprene activity: less production by vegetation and more consumption by soils.

In addressing how well climate models predict the response of isoprene emission to future global change, Monson *et al.* (2007) note such predictions “probably contain large errors” because “the fundamental logic of such models is that changes in NPP [net primary production] will produce more or less biomass capable of emitting isoprene, and changes in climate will stimulate or inhibit emissions per unit of biomass.” The 12 researchers continue, “these models tend to ignore the discovery that there are direct effects of changes in the atmospheric CO₂ concentration on isoprene emission that tend to work in the opposite direction to that of stimulated NPP.” Their results show, in their words, “that growth in an atmosphere of elevated CO₂ inhibited the emission of isoprene at levels that completely compensate for possible increases in emission due to increases in aboveground NPP.” Monson *et al.* state, “to a large

extent, the modeling has ‘raced ahead’ of our mechanistic understanding of how isoprene emissions will respond to the fundamental drivers of global change.” They conclude, “without inclusion of these effects in the current array of models being used to predict changes in atmospheric chemistry due to global change, one has to question the relevance of the predictions.”

Arneth *et al.* (2008) used a mechanistic isoprene-dynamic vegetation model of European woody vegetation to “investigate the interactive effects of climate and CO₂ concentration on forest productivity, species composition, and isoprene emissions for the periods 1981–2000 and 2081–2100,” which included a parameterization of the now-well-established direct CO₂-isoprene inhibition phenomenon described in the studies discussed above. They found “across the model domain,” the CO₂-isoprene inhibition effect “has the potential to offset the stimulation of [isoprene] emissions that could be expected from warmer temperatures and from the increased productivity and leaf area of emitting vegetation.”

In something of a challenge to this thesis, Kiendler-Scharr *et al.* (2009) “present evidence from simulation experiments conducted in a plant chamber that isoprene can significantly inhibit new particle formation.” The significance of this finding, they write, derives from the fact that “the most abundant volatile organic compounds emitted by terrestrial vegetation are isoprene and its derivatives, such as monoterpenes and sesquiterpenes” and that (as described in the “This Issue” abstract section of *Nature* (p. 311)) “these compounds are involved in the formation of organic aerosols [the “new particles” mentioned by them], which act as ‘seeds’ for cloud formation and hence as cooling agents via an effect on radiative forcing.” Moreover, as Ziemann (2009) explained in a “News & Views” article that discusses the Kiendler-Scharr *et al.* paper, “clouds formed at higher CCN [cloud condensation nuclei] concentrations have more and smaller drops than those formed at lower concentrations, and so reflect more sunlight and are longer-lived—effects that, at the global scale, enhance the planetary cooling that counteracts some of the warming caused by greenhouse gases.” Thus, if vegetative isoprene emissions were to increase, driven directly by rising temperatures and/or indirectly by warming-induced changes in the species composition of boreal forests (as further suggested by Ziemann), the resulting decrease in CCN concentrations “could lead to

increased global-warming trends,” as suggested by Kiendler-Sharr in a “Making the Paper” article in the same issue of *Nature* (p. 313).

The story propounded by these facts may seem to deliver a devastating blow to the negative CO₂-induced isoprene feedback, yet, and almost as an afterthought, Ziemann writes consideration also should be given to what he calls “the potential suppression of terpene emissions by elevated carbon dioxide concentrations.” When this is done, as demonstrated by the multiple sets of observational data of Young *et al.* (2009) and plotted in Figure 2.5.2.2.1.1, it becomes clear that rising atmospheric CO₂ concentrations will significantly decrease isoprene emissions from plants and thereby increase cloud condensation nuclei concentrations and lead to a cooling of the planet.

Wilkinson *et al.* (2009) grew three-year-old cottonwood trees and two-year-old aspen trees in controlled-environment chambers maintained for several weeks at atmospheric CO₂ concentrations of 400 and 800 ppm, with the aspen trees also exposed to CO₂ concentrations of 600 and 1,200 ppm. In addition, they grew two-year-old sweetgum and eucalyptus trees in another controlled-environment facility maintained at CO₂ concentrations of 240 and 380 ppm. They measured the isoprene emission rate (IS) of the trees’ leaves, finding “IS was approximately 30% and 18% lower, respectively, for eucalyptus and sweetgum trees grown at 520 ppm CO₂, compared with trees grown at 240 ppm CO₂.” The nine researchers also found the cottonwood and aspen trees “exhibited a 30–40% reduction in isoprene emission rate when grown at 800 ppm CO₂, compared with 400 ppm CO₂,” and the aspen trees “exhibited a 33% reduction when grown at 1200 ppm CO₂, compared with 600 ppm CO₂.”

Wilkinson *et al.* then “used current models of leaf isoprene emission to demonstrate that significant errors occur if the CO₂ inhibition of isoprene is not taken into account,” developing in the process “a quantitative algorithm that can be used to scale IS at the leaf level to changes in atmospheric and intercellular CO₂” that can be “incorporated into larger-scale models that aim to predict regional or global patterns in IS,” which can further be used to address “important questions concerning atmospheric chemistry in the face of future global change projections.”

In a related paper published in the same issue of *Global Change Biology*, Heald *et al.* (2009) incorporated an empirical model of observed isoprene

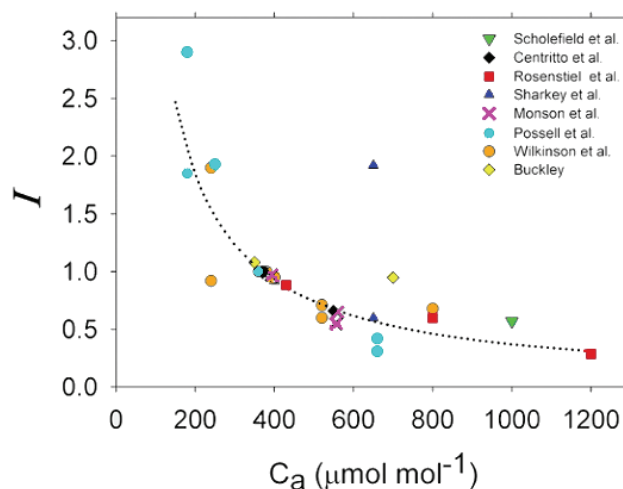


Figure 2.5.2.2.1.1. Field and laboratory observations of leaf isoprene emissions (I) from plants grown in a variety of atmospheric CO₂ concentrations (Ca), normalized to a value of unity at Ca = 370 μmol mol⁻¹ (= 370 ppm). Reprinted with permission from Young, P.J., Arneth, A., Schurgers, G., Zeng, G., and Pyle, J.A. 2009. The CO₂ inhibition of terrestrial isoprene emission significantly affects future ozone projections. *Atmospheric Chemistry and Physics* 9: 2793–2803.

emissions response to changes in atmospheric CO₂ concentration in the long-term growth environment and short-term changes in intercellular CO₂ concentrations into a biogenic emission model embedded within the Community Land Model of the global NCAR Community Climate System Model. They found “the large increases in future isoprene emissions typically predicted in models, which are due to a projected warmer climate, are entirely offset by including the CO₂ effects.”

Lathiere *et al.* (2010) utilized the Model of Emissions of Gases and Aerosols from Nature (MEGAN), developed by Guenther *et al.* (2006), to calculate changes in isoprene emissions from the terrestrial biosphere in response to climate change, atmospheric CO₂ increase, and land use change throughout the twentieth century. They found between 1901 and 2002, climate change at the global scale “was responsible for a 7% increase in isoprene emissions,” but “rising atmospheric CO₂ caused a 21% reduction,” and “by the end of the 20th century, anthropogenic cropland expansion had the largest impact, reducing isoprene emissions by 15%.” As a result, “overall, these factors combined to cause a 24% decrease in global isoprene emissions during the 20th century.” The three scientists also warned “the possible rapid expansion of biofuel production with

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high isoprene-emitting plant species (e.g., oil palm, willow and poplar) may reverse the trend by which conversion of land to food crops leads to lower isoprene emissions.”

The research reviewed here strongly suggests the ongoing rise in atmospheric CO₂ concentrations will reduce atmospheric isoprene concentrations, which will lead to increases in cloud condensation nuclei concentrations, ultimately leading to a cooling of the planet—a negative feedback ignored by most proponents of the CO₂-induced global warming theory.

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2.5.3 Non-Biological

2.5.3.1 Anthropogenic

There are several ways the activities of humanity lead to the creation of aerosols that have the potential to alter Earth's radiation balance and affect its climate. Contrails created in the wake of emissions from jet aircraft are one example. Minnis *et al.* (2004) have calculated nearly all of the surface warming observed over the United States between 1975 and 1994 (0.54°C) may be explained by aircraft-induced increases in cirrus cloud coverage over that period. If true, this would imply little or none of the observed U.S. warming during that period could be attributed to the increase in the air's CO₂ content.

Ship tracks—bright streaks that form in layers of marine stratus clouds—are another example. Created by emissions from ocean-going vessels, these persistent and highly reflective linear patches of low-level clouds tend to cool the planet (Ferek *et al.*, 1998; Schreier *et al.*, 2006).

Schreier *et al.* (2006) developed an algorithm “to determine ship tracks from satellite data in an automated way,” after which “a scene on 10 February 2003 was chosen to extract the optical and microphysical cloud modifications from ship emissions using Terra-MODIS satellite data,” in which “a combination of the semi-analytical approach SACURA [Kokhanovsky *et al.*, 2003] with a look-up-table for optically thin clouds [Mayer and Kylling, 2005] was used to calculate cloud properties.” The analysis revealed, on average, cloud “optical thickness was increased from 20.7 up to 34.6 and the effective [droplet] radius was decreased from 13.2 μm to 10.1 μm,” while “the calculated average droplet number concentration increased from 79 up to 210 cm⁻³.”

Using these numbers to calculate changes in the radiative energy budget above and below the marine stratus clouds influenced by the ship emissions, Schreier *et al.* (2006) reported “a decrease of 43.2 W m⁻² for the surface radiation below the ship tracks and an increase of 40.8 W m⁻² for the increased reflectivity at the top of the atmosphere.” They note, “if the whole low-cloud area with 6.7% ship-track-pixels is taken into account, a decrease in the radiation at the surface of 2.1 W m⁻² and an increase of 2.0 W m⁻² in backscattered solar radiation [is] found.” The eight German researchers thus conclude, “modifications of clouds by international shipping can be an important contributor to climate on a local scale.”

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As for the global scale, averaged over the surface of Earth both day and night and over the year, Capaldo *et al.* (1999) calculated this phenomenon creates a mean negative radiative forcing of -0.16 W m^{-2} in the Northern Hemisphere and -0.06 W m^{-2} in the Southern Hemisphere. Compare these values to a much smaller estimate from the IPCC (compare the W m^{-2} with the mW m^{-2} unit), which concluded in its most recent assessment, “the global radiative forcing of visible ship tracks has been estimated from satellite and found to be insignificant at about -0.5 mW m^{-2} ” (p. 7-39 of Chapter 7, Second Order Draft of AR5, dated October 5, 2012). For additional context, the IPCC calculates a positive radiative forcing of approximately 4 W m^{-2} due to a 300 ppm increase in the atmosphere’s CO_2 concentration.

In some cases, the atmosphere over the sea also carries a considerable burden of anthropogenically produced aerosols from terrestrial sites. In recent years, attention to this topic has centered on highly polluted air from south and southeast Asia that makes its way over the northern Indian Ocean during the dry monsoon season. There has been much discussion about the impact of this phenomenon on regional climates. Norris (2001) looked at cloud cover as the ultimate arbiter of the competing hypotheses, finding daytime low-level oceanic cloud cover increased substantially over the last half of the past century in both the Northern and Southern Hemispheres at essentially all hours of the day. This finding is indicative of a pervasive net cooling effect.

Aerosol-generating human activities also have a significant impact on local, as well as more wide-ranging, climatic phenomena over land. Sahai (1998) pointed out although suburban areas of Nagpur, India had warmed over recent decades, the central part of the city had cooled, especially during the day, because of “increasing concentrations of suspended particulate matter.” Similarly, outside but adjacent to industrial complexes in the Po Valley of Italy, Facchini *et al.* (1999) found water vapor was more likely to form on aerosols altered by human-produced organic solutes, and this phenomenon led to the creation of more numerous and more highly reflective cloud droplets that had a tendency to cool the surface below them.

Rosenfeld (2000) studied pollution tracks downwind of urban/industrial complexes in Turkey, Canada, and Australia. His findings indicate the clouds comprising these pollution tracks were composed of small droplets that suppressed

precipitation by inhibiting further coalescence and ice precipitation formation. In commenting on this research, Toon (2000) notes when clouds are composed of smaller droplets, they will not “rain out” as quickly and therefore will last longer and cover more of Earth, both of which effects tend to cool the globe.

In reviewing these and other advances in the field of anthropogenic aerosol impacts on clouds, Charlson *et al.* (2001) note droplet clouds “are the most important factor controlling the albedo (reflectivity) and hence the temperature of our planet.” They also note manmade aerosols “have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases” and “both the forcing [of this impetus for cooling] and its magnitude may be even larger than anticipated.” Failure to include these important phenomena in climate change deliberations “poses additional uncertainty beyond that already recognized by the Intergovernmental Panel on Climate Change, making the largest uncertainty in estimating climate forcing even larger.”

Devasthale *et al.* (2005) examine the possible influence of aerosols on cloud-top temperature (CTT) using long-term satellite brightness temperatures from the Advanced Very High Resolution Radiometer onboard the NOAA satellite series over eastern and central Europe. In order to identify and quantify possible aerosol-induced changes, CTTs were compared for two four-year periods of distinctively higher (1985–1998) and lower (1997–2000) anthropogenic pollution loads.

Devasthale *et al.* report the results of the analysis were “astonishing.” For all types and levels of clouds analyzed, over both land and sea, lower CTTs were observed during the higher pollution levels of the late 1980s, such that the tops of low- and medium-level clouds were more than 2°C colder during that period, and about 4°C colder if convective clouds were included. Regions of greater CTT variability coincided with metropolitan areas and industrial centers that contained higher concentrations of particulate matter and black carbon inventories.

One implication of these findings, the researchers noted, is the “observed indirect aerosol effect in the thermal infrared on regional scale could be equally important if not dominant over the solar radiation changes and thus needs to be further investigated for other regions.” This effect may be large enough to have had a significant influence on the near-surface

and tropospheric temperature histories of the past few decades.

Another pertinent observation comes from Stanhill and Cohen (2001), who reviewed numerous solar radiation measurement programs around the world to see if there had been any trend in the mean amount of solar radiation falling on the surface of Earth over the past half-century. They determined there was a significant 50-year downward trend in this parameter that “has globally averaged $0.51 \pm 0.05 \text{ W m}^{-2}$ per year, equivalent to a reduction of 2.7 percent per decade, [which] now totals 20 W m^{-2} .” They conclude the most probable explanation for this observation “is that increases in man-made aerosols and other air pollutants have changed the optical properties of the atmosphere, in particular those of clouds.”

This surface-cooling influence falls in the mid-range of a similar solar radiative perturbation documented by Satheesh and Ramanathan (2000) in their study of the effects of human-induced pollution over the tropical northern Indian Ocean, where they determined “mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to 30 W m^{-2} .” Hence, the decline in solar radiation reception discovered by Stanhill and Cohen could well be real, representing a strong counter-influence to the enhanced greenhouse effect produced by the increase in atmospheric CO_2 concentration.

Alpert *et al.* (2005) hypothesized the dimming of the 1950s through 1980s could be explained by the anthropogenic release of pollutants, such as sulfates, nitrates, and black carbon, which acted to reduce the amount of solar radiation received at Earth’s surface. To test this theory, for the 25-year period 1964–1989 the authors examined trends in the surface receipt of solar radiation at 144 urban sites (population greater than 100,000 persons) and 174 rural sites (population less than 100,000 persons) for various latitudinal bands as well as for the entire globe. For the globe as a whole, they found both urban and rural locations showed a decline in surface solar radiation over the period of study. The rate of decline at the urban locations was approximately 2.6 times larger than that observed at the rural locations ($-0.41 \text{ W m}^{-2}\text{yr}^{-1}$ vs. $-0.16 \text{ W m}^{-2}\text{yr}^{-1}$). In addition, a sharper decline in surface solar radiation receipt was found between 10°N and 40°N , the latitudinal zone nearly coincident with the zone of maximum fossil fuel emissions in the Northern Hemisphere reported by Stanhill and Cohen (2001) for the period 1960–1990. The latitude band

from 15°S to 15°N displayed the opposite trend: Instead of dimming, this region experienced a brightening of $0.58 \text{ W m}^{-2}\text{yr}^{-1}$, a finding consistent with those of Pinker *et al.* (2005), who reported a persistent increase in surface solar radiation over the latitudes 20°S to 20°N based on satellite data.

According to Alpert *et al.*, their findings suggest solar dimming is “significantly dominated by large cities’ contributions to the atmospheric pollution” and it is “essentially a local phenomenon, observed only in a limited part of the total land area.” The magnitudes of the original dimming and the more recent brightening are much greater than the magnitude of the increase in total greenhouse-gas-induced radiative forcing over this period, yet another good reason to suggest the global instrumental temperature record may be significantly “polluted” in a way that has heretofore not been adequately appreciated.

In a more recent study, Ruckstuhl *et al.* (2008) presented “observational evidence of a strong decline in aerosol optical depth over mainland Europe during the last two decades of rapid warming”—when air temperatures rose by about 1°C after 1980—via analyses of “aerosol optical depth measurements from six specific locations and surface irradiance measurements from a large number of radiation sites in Northern Germany and Switzerland.” They observed a decline in aerosol concentration of up to 60 percent and found “a statistically significant increase of solar irradiance under cloud-free skies since the 1980s.” The value of the direct aerosol effect of this radiative forcing was approximately 0.84 W m^{-2} ; when combined with the concomitant cloud-induced radiative forcing of about 0.16 W m^{-2} , it led to a total radiative surface climate forcing over mainland Europe of about 1 W m^{-2} that “most probably strongly contributed to the recent rapid warming in Europe.” Cleaning up significantly polluted skies, it seems, can provide an even greater impetus for climate warming than does the carbon dioxide concurrently emitted to them.

Mission *et al.* (2005) note “anthropogenic aerosols have more efficient optical extinction for light than natural aerosols (Carrico *et al.*, 2003; Seinfeld and Pandis, 1998) and are responsible for about half of the extinction and scattering of light by particles globally (Houghton *et al.*, 2001).” Increases in atmospheric aerosols, while reducing the total flux of solar radiation received at Earth’s surface, increase the flux of *diffuse* light received there, such that the volume of shade within forest canopies is so greatly

decreased it enhances whole-canopy photosynthesis to the point that more CO₂ is extracted from the atmosphere under high-aerosol-content conditions than under more pristine conditions (see, for example, the work of Roderick *et al.* (2001), Law *et al.* (2002), and Gu *et al.* (2003)).

Mission *et al.* determined the recurrent influx of air pollution from California's Central Valley to the Blodgett Forest site during summer afternoons decreased total irradiance there by 11 percent from what it was at comparable times relative to solar noon in the mornings. Diffuse radiation, on the other hand, was 24 percent higher in the afternoons; this effect predominated to the extent that "aerosol loading caused net uptake of CO₂ by the forest to increase by 8% in the afternoon." The presence of atmospheric aerosols not only reduces the receipt of solar radiation at Earth's surface, providing an impetus for cooling, it also enhances forest rates-of-removal of CO₂ from the atmosphere, which over the long term provides yet another cooling effect.

Su *et al.* (2011) describe and demonstrated how reactive nitrogen compounds, such as those found in synthetic fertilizers, may be acted upon by soil microbes to produce nitrites in both agricultural soils and the soils of forests and boreal regions; and they show how the photolysis of the nitrous acid (HONO) consequently found in these soils can produce up to ~30 percent of the atmosphere's total OH concentration. Their findings explain the origin, size, and diurnal variation of field observations that had previously suggested there was a large unknown source of HONO having the characteristics they identified.

The phenomenon described by the ten scientists plays an important role in the atmosphere's photochemistry, which in turn plays a key role in the planet's energy balance, because OH radicals act as precursors of aerosols that can contribute to climate change by reflecting a portion of the incoming solar radiation from the Sun back to space, thereby exerting a cooling influence on the planet. To quote the international team of researchers, "because of enhanced fertilizer use and soil acidification in developing countries (Guo *et al.*, 2010), the release of HONO from soil nitrite might strongly increase in the course of global change, resulting in elevated OH concentrations and amplified oxidizing capacity of the lower troposphere," which would tend to impede the warming that helped to initiate the phenomenon, illustrating yet another of the "checks and balances"

built into Earth's highly complex climatic system.

In further commentary on Su *et al.*'s findings, Kulmala and Petaja (2011) rhetorically asked: "What would happen if global HONO emissions from soil doubled within the next 25 years?" In answer, they said it "could increase the atmosphere's ability to cleanse itself of volatile compounds such as methane," a powerful greenhouse gas. Perhaps that is why atmospheric methane concentrations have risen at a much slower rate over the prior two decades than they had previously risen, as has been reported by Simpson *et al.* (2002), Dlugokencky *et al.* (2003), Khalil *et al.* (2007), Schnell and Dlugokencky (2008), and other researchers.

Anthropogenic aerosols clearly affect climate in ways that rival or even exceed the likely effect of rising atmospheric CO₂ levels. As great progress has been made in recent decades to reduce air pollution in developed countries, it is entirely possible the lion's share of warming has been produced by the removal from the atmosphere of true air pollutants.

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2.5.3.1.1 Black Carbon

Kaspari *et al.* (2011) point out “black carbon (BC, the absorbing component of soot) produced by the incomplete combustion of biomass, coal and diesel fuels can significantly contribute to climate change by altering the Earth’s radiative balance,” noting “BC is estimated to have 55% of the radiative forcing effect of CO₂ (Ramanathan and Carmichael, 2008),” in line with the approximately 1 W m⁻² radiative forcing of black carbon reported by Hansen (2002).

Kaspari *et al.* further note BC remains “one of the largest sources of uncertainty in analyses of climate change.” They developed a high-resolution BC record spanning the period AD 1860–2000 from a Mt. Everest ice core extracted from the East Rongbuk glacier located on the mountain’s northeast ridge on the north slope of the Himalaya, which record, in their words, “provides the first pre-industrial-to-present record of BC concentrations from the Himalayas.” The seven scientists determined “BC concentrations from 1975–2000 relative to 1860–1975 have increased approximately threefold, indicating that BC from anthropogenic sources is being transported to high elevation regions of the Himalaya.” In addition, “the increase in Everest BC during the 1970s is simultaneous with a rise in BC emissions as estimated from historical records of energy-related combustion in South Asia and the Middle East (Bond *et al.*, 2007).”

Kaspari *et al.* said their findings suggest “a reduction in BC emissions may be an effective means to reduce the effect of absorbing impurities on snow albedo and melt, which affects Himalayan glaciers and the availability of water resources in major Asian rivers.” Ramanathan and Carmichael (2008) note the majority of BC emissions (60 percent) arise from “cooking with biofuels such as wood, dung and crop

residue” and from “open biomass burning (associated with deforestation and crop residue burning),” while Venkataraman *et al.* (2005) note control of BC emissions through cleaner cooking technologies alone could help in “reducing health risks to several hundred million users.” It would seem reducing biofuel sources of BC emissions would be a prudent goal.

Also working in Asia, Kopacz *et al.* (2011) point out “the Himalayas and the Tibetan Plateau, also collectively known as the Third Pole, represent a large area of seasonal and permanent snow cover,” which is “surrounded by growing emissions of Asian air pollutants.” They note observations of black carbon (BC) content in snow “show a rapidly increasing trend,” citing the work of Xu *et al.* (2009). For their own study of the subject, Kopacz *et al.* used a global chemical transport model to identify the location from which the BC arriving at a variety of locations in the Himalayas and the Tibetan Plateau originates, after which they calculated its direct and snow-albedo radiative forcings.

According to the six U.S. scientists, the results indicated “emissions from northern India and central China contribute the majority of BC to the Himalayas,” and “the Tibetan Plateau receives most BC from western and central China, as well as from India, Nepal, the Middle East, Pakistan and other countries.” In addition, they report the radiative forcing due to the direct effect of BC at five glacier sites has “a global annual mean of +0.32 W/m², while “the local monthly mean radiative forcing due to changes in snow-albedo ranges from +3.78 to +15.6 W/m².”

Researching a much larger region of the globe, for the period 1875–2000, Novakov *et al.* (2003) presented “estimates of past fossil-fuel BC emissions from the United States, United Kingdom, Germany, Soviet Union, India and China,” which nations in 1990 accounted for “about 70% and 60%, respectively, of the world consumption of coal and diesel fuel, which are the principal BC-producing fossil-fuels.” The authors report a “rapid increase [in BC] in the latter part of the 1800s, ... leveling off in the first half of the 1900s, and ... re-acceleration in the past 50 years as China and India developed.” They estimate the climate forcing by BC aerosols to be “of the order of +0.5 W m⁻²,” two-thirds greater than the +0.3 W m⁻² forcing estimate of the IPCC (p. 18 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). They also note

“estimates of the current anthropogenic BC climate forcing are of the order of 1/3 to 1/2 of the current CO₂ forcing.”

It is apparent that modern trends in BC have presented a significant radiative forcing across many parts of the globe meriting serious examination and future study, especially by the IPCC, in order to correctly interpret past, present, and future climate trends.

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2.5.3.2 Natural

We conclude this section with a brief discussion of a non-biological, naturally produced aerosol: dust.

Dust is about as natural and ubiquitous a substance as there is. One might expect scientists to have a pretty good handle on what it does to Earth's climate, but that is not the case.

Sokolik (1999), with the help of nine colleagues, summarized the sentiments of a number of scientists who had devoted their lives to studying the subject. According to Sokolik, state-of-the-art climate models “rely heavily on oversimplified parameterizations” of many important dust-related phenomena, “while ignoring others.” As a result, Sokolik concludes “the magnitude and even the sign of dust net direct radiative forcing of climate remains unclear.”

Sokolik says there are a number of unanswered questions about airborne dust: How does one quantify dust emission rates from natural and anthropogenic sources with required levels of temporal and spatial resolution? How does one accurately determine the composition, size, and shape of dust particles from ground-based and aircraft measurements? How does one adequately measure and model light absorption by mineral particles? How does one link the ever-evolving optical, chemical, and physical properties of dust to its life cycle in the air? How does one model complex multi-layered aerosol stratification in the dust-laden atmosphere? And how does one quantify airborne dust properties from satellite observations?

In discussing these questions, Sokolik observed what is currently known, or believed to be known, about dust emissions “is largely from micro-scale experiments and theoretical studies.” He suggests new global data sets are needed to provide “missing information” on input parameters (such as soil type, surface roughness, and soil moisture) required to model dust emission rates, and improvements in methods used to determine some of these parameters are also “sorely needed.” How to adequately measure light absorption by mineral particles is an “outstanding problem,” he notes, and it “remains unknown how well these measurements represent the light absorption by aerosol particles suspended in the atmosphere.” It is easy to understand why Sokolik concludes “a challenge remains in relating dust climatology and the processes controlling the evolution of dust at all relevant spatial/temporal scales needed for chemistry and climate models.”

Vogelmann *et al.* (2003) reiterated that “mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux [of] between 7 and 25 W m⁻² (Sokolik *et al.*, 1998),” while at the same time acknowledging “only a few large-scale climate

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models currently consider aerosol IR effects (e.g., Tegen *et al.*, 1996; Jacobson, 2001) despite their potentially large forcing.” Vogelmann *et al.* “use[d] high-resolution spectra to obtain the IR radiative forcing at the surface for aerosols encountered in the outflow from northeastern Asia,” based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. This work led them to conclude, “daytime surface IR forcings are often a few W m^{-2} and can reach almost 10 W m^{-2} for large aerosol loadings,” which values, in their words, “are comparable to or larger than the 1 to 2 W m^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times.” Vogelmann *et al.* conclude their results “highlight the importance of aerosol IR forcing which should be included in climate model simulations.”

Another aspect of the dust-climate connection centers on the African Sahel, which has figured prominently in discussions of climate change since it began to experience extended drought conditions in the late 1960s and early ‘70s. Initial studies of the drought attributed it to anthropogenic factors such as overgrazing of the region’s fragile grasses, which tends to increase surface albedo, which was envisioned to reduce precipitation, resulting in a further reduction in the region’s vegetative cover (Otterman, 1974; Charney, 1975). That scenario was challenged by Jackson and Idso (1975) and Idso (1977) on the basis of empirical observations, while Lamb (1978) and Folland *et al.* (1986) attributed the drought to large-scale atmospheric circulation changes triggered by multidecadal variations in sea surface temperature.

Building on the insights provided by these latter investigations, Giannini *et al.* (2003) presented evidence based on an ensemble of integrations with a general circulation model of the atmosphere—forced only by the observed record of sea surface temperature—which suggests the “variability of rainfall in the Sahel results from the response of the African summer monsoon to oceanic forcing amplified by land-atmosphere interaction.” The success of this analysis led them to attribute “the recent drying trend in the semi-arid Sahel ... to warmer-than-average low-latitude waters around Africa, which, by favoring the establishment of deep convection over the ocean, weaken the continental

convergence associated with the monsoon and engender widespread drought from Senegal to Ethiopia.” They further conclude “the secular change in Sahel rainfall during the past century was not a direct consequence of regional environmental change, anthropogenic in nature or otherwise.”

In a companion article, 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. They noted the 2001 IPCC report “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.” But “there is little firm evidence to support either of these assumptions,” they write.

Huang *et al.* (2011) calculated bulk sediment fluxes and analyzed grain-size distributions of detrital sediments over the past two millennia from an 11.12 meter sediment core obtained from Asia’s Aral Sea, after which they compared their results with the temperature history of the Northern Hemisphere produced by Mann and Jones (2003), with an emphasis “placed on the variations at the transition from the Medieval Warm Period (MWP) to Little Ice Age (LIA) since this period is the most pronounced climatic transformation during the last millennium,” citing in this regard the studies of Yang *et al.* (2002), Trouet *et al.* (2009), and Chen *et al.* (2010).

The comparison revealed “a remarkably low deposition [of dust] during AD 1–350,” which would have been part of the Roman Warm Period; “a moderately high value from AD 350–720,” which corresponds to the Dark Ages Cold Period; “a return to a relatively low level between AD 720 and AD 1400,” which includes the Medieval Warm Period; “an exceptionally high deposition from AD 1400 to the 1940s,” which includes the Little Ice Age; and what they refer to as “an abnormally low value since the 1940s,” when the Current Warm Period may be considered to have begun.

The four researchers state the temporal variations in the dust deposition are consistent with changes in the “mean atmospheric temperature of the northern hemisphere during the past 2000 years, with low/high annual temperature anomalies corresponding to high/low dust supplies in the Aral Sea sediments, respectively,” reinforcing the reality of a non-CO₂-induced forcing of Earth’s surface air temperature.

Clearly, much remains to be learned about the climatic impacts of dust, whose radiative impacts, the IPCC has concluded, “are too uncertain” to include in their estimates of radiative forcing (p. 18 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

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2.6 Other Forcings and Feedbacks

Researchers have identified other forcings and feedbacks about which little is currently known, or acknowledged by the IPCC, but which may ultimately prove to be important drivers of climate change. Other variables, currently considered insignificant, may with changing conditions become important as thresholds change. This section explores some of those phenomena described in the peer-reviewed scientific literature.

2.6.1 Carbon Sequestration

As the carbon dioxide content of the air continues to rise, nearly all of Earth’s plants will respond by increasing their photosynthetic rates and producing more biomass. These increases in productivity will likely lead to greater amounts of carbon sequestration in both above- and below-ground plant parts as well as in soils. But how powerful is the carbon sequestering ability of Earth’s vegetation? Is it

powerful enough to slow the rise of atmospheric CO₂ to provide a natural brake on CO₂-induced global warming? How is it affected by an increase in air temperature? This section reviews the results of studies that have addressed these and other important questions pertaining to biospheric carbon sequestration.

Early investigation into this topic occurred more than two decades ago when many people were concerned the air's CO₂ content would rise in direct proportion to the magnitude of humanity's increasing emissions of carbon dioxide. Idso (1991a,b) felt otherwise and predicted the air's CO₂ content would rise at a rate that would be a declining percentage of anthropogenic CO₂ emissions, hypothesizing the productivity of Earth's plant life would rise in response to the ongoing increase in the air's CO₂ content—due to the well-known aerial fertilization effect of carbon dioxide—thereby resulting in ever more CO₂ being removed from the atmosphere each year. Vindication of Idso's thesis came via real-world data a decade later, with Wofsy (2001) reporting in a "Climate Change" article in *Science* that "emission rates of CO₂ from combustion of fossil fuel have increased almost 40 percent in the past 20 years, but the amount of CO₂ accumulating in the atmosphere has stayed the same or even declined slightly."

Other studies also have demonstrated this increased ability of the biosphere to sequester carbon from the atmosphere as the air's CO₂ concentration has gradually risen over the past few decades and throughout the Industrial Revolution. Working in the coterminous United States, for example, Pacala *et al.* (2001) found estimates of the country's 48-state carbon sequestering power have grown significantly over the past several years, from a range of 0.08–0.35 x 10¹⁵ grams of carbon per year (Pg C yr⁻¹) in the 1980s to a range of 0.37–0.71 Pg C yr⁻¹ by the turn of the century, with some evidence suggesting values as high as 0.81–0.84 Pg C yr⁻¹ (Fan *et al.*, 1998).

Similarly, Fang *et al.* (2001) reported increases in carbon sequestration in China. With a little help from the Chinese government via several "ecological restoration projects" aimed primarily at afforestation and reforestation, the world's most populous country has turned around what had been a losing proposition with respect to carbon capture by forests, where an average of 0.021 Pg C yr⁻¹ had been sequestered there for about the last two decades of their study.

Harrison *et al.* (2008) used the Joint UK Land Environment Simulator (JULES), a land surface and

carbon cycle model, to simulate the biospheric carbon balance of Europe and its sensitivity to rising CO₂ and changes in climate experienced over the period 1948–2005. Over the 57-year period of their study, Harrison *et al.* report "the impact of climate changes since 1948 has been to decrease the ability of Europe to store carbon by 97 TgC year⁻¹," but "the effect of rising atmospheric CO₂ has been to stimulate increased uptake and storage." This latter phenomenon apparently was so strong it led, in their words, to "a net increase in stored carbon of 114 TgC year⁻¹."

In addition to stimulating *terrestrial* carbon storage, the rising atmospheric CO₂ concentration also should enhance *oceanic* carbon sequestration. Wolf-Gladrow *et al.* (1999) reviewed the direct effects of atmospheric CO₂ enrichment on marine biota and oceanic "carbon pumps," concluding an increase in the air's CO₂ content should increase the capacity of Earth's oceans to take up and store more atmospheric CO₂.

Working on both fronts (land and ocean), Joos and Bruno (1998) utilized ice cores and direct observations of atmospheric CO₂ and ¹³C to reconstruct the histories of terrestrial and oceanic uptake of anthropogenic carbon over the past two centuries. During the initial portion of this period and persisting into the first decades of the past century, they determined the biosphere as a whole supplied carbon to the atmosphere. Thereafter, however, the biosphere became a carbon sink. In further scrutinizing their data, they note the current global carbon sink has been growing in magnitude for at least the past hundred years.

In reviewing the progress of research dealing with the global carbon cycle, Tans and White (1998) conclude "early estimates of huge losses of carbon from plants and soils due to biomass burning and deforestation have recently given way to the idea of a terrestrial biosphere nearly balanced (globally) with respect to carbon." After analyzing O₂/N₂ measurements of background air collected at Cape Grim, Tasmania from 1978 to 1997, Langenfelds *et al.* (1999) determined the surface fluxes of carbon over this 19-year period were "essentially in balance." In other words, essentially all of the carbon released to the air as a consequence of the activities of man was removed from the atmosphere by the biological activities of predominantly terrestrial vegetation.

Khatiwala *et al.* (2009) note the world's oceans play "a crucial role in mitigating the effects of [rising

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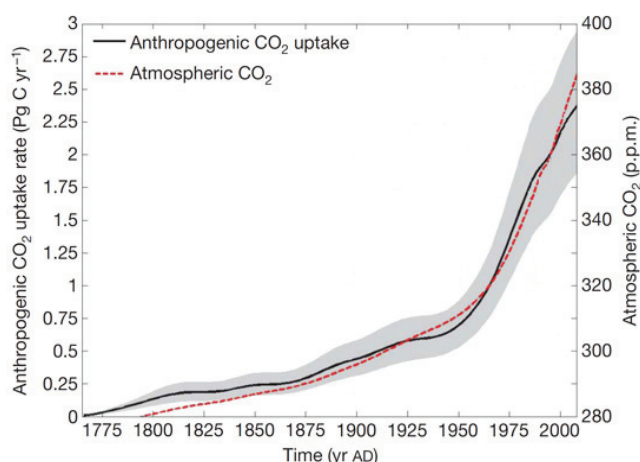


Figure 2.6.1.1. Atmospheric CO₂ concentration and oceanic uptake rate of anthropogenic carbon (with shaded error envelope) plotted against time. Adapted from Khatiwala, S. Primeau, F., and Hall, T. 2009. Reconstruction of the history of anthropogenic CO₂ concentrations in the ocean. *Nature* **462**: 346–349.

atmospheric CO₂] to the climate system.” They derived “an observationally based reconstruction of the spatially-resolved, time-dependent history of anthropogenic carbon in the ocean over the industrial era [AD 1765 to AD 2008],” based on the known history of the air’s CO₂ concentration and analyses of the oceanic transport of “a suite of well sampled oceanic tracers such as chlorofluorocarbons, natural ¹⁴C, temperature, and salinity from the GLODAP and World Ocean Atlas databases.” The three U.S. researchers determined the amount of anthropogenic CO₂ taken up by the world’s oceans has been increasing with the passage of time, pretty much in phase with the atmosphere’s ever-increasing CO₂ concentration, as shown in Figure 2.6.1.1.

In addition, Khatiwala *et al.* note after the sharp increase in the anthropogenic CO₂ uptake rate after the 1950s there has been “a small decline in the rate of increase in the last few decades.” This latest deviation of the oceanic CO₂ uptake rate (from its correlation with the atmosphere’s CO₂ concentration) is similar to those of prior such deviations, which have been of both a positive and negative nature. The size of the error envelope (the shaded area in Figure 2.6.1.1) associated with the anthropogenic CO₂ uptake rate allows for the possibility that its correlation with the atmosphere’s CO₂ concentration

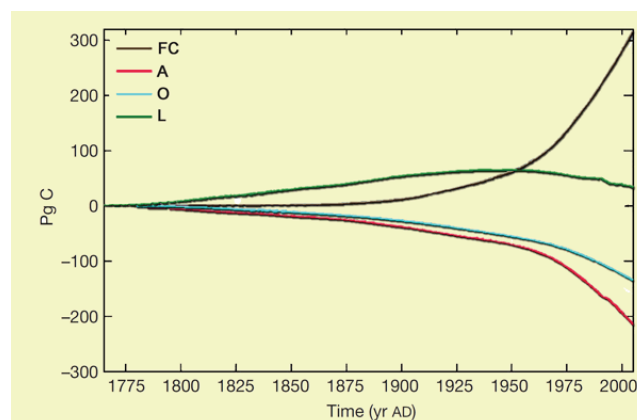


Figure 2.6.1.2. The evolution of anthropogenic-produced carbon originating from fossil fuel use and cement production (FC), together with the similar evolution of the three anthropogenic carbon sinks—atmosphere (A), ocean (O), and land (L)—between AD 1765 and 2005. Adapted from Khatiwala, S. Primeau, F., and Hall, T. 2009. Reconstruction of the history of anthropogenic CO₂ concentrations in the ocean. *Nature* **462**: 346–349.

could have been essentially perfect from about the 1860s through and including the present time.

Writing about Khatiwala *et al.*’s work in the November 19, 2009 issue of *The New York Times*, Sindya Bhanoo presented a distinctly pessimistic slant to the scientists’ findings, stating the growth in the ocean’s uptake rate of anthropogenic carbon “has slowed since the 1980s, and markedly so since 2000,” implying “the research suggests that the seas cannot indefinitely be considered a reliable ‘carbon sink’ as humans generate heat-trapping gases.” Bhanoo quotes Khatiwala himself as saying the recent trend to lower values of the ocean’s uptake rate of anthropogenic carbon “implies that more of the emissions will remain in the atmosphere.”

Quite to the contrary, however, the finely intertwined relationship of the two parameters of Figure 2.6.1.1 clearly demonstrates, well within the accuracy of the various measurements involved, that the global ocean is constantly adjusting its uptake rate of anthropogenic carbon on multi-decadal time scales to “keep up” with the rate at which the air’s CO₂ content rises in response to anthropogenic carbon inputs.

In light of their independent assessment of the absorption of anthropogenic CO₂ by the global ocean, and knowing the historical record of fossil fuel use

and cement production as well as the concomitant change in the atmosphere's CO₂ content, Khatiwala *et al.* also calculated, as a residual, the net absorption of anthropogenic CO₂ by Earth's land surface since the inception of the Industrial Revolution; this latter calculation is presented in Figure 2.6.1.2.

The authors' results indicate "the terrestrial biosphere was a source of anthropogenic carbon until the 1940s, roughly in line with previous model-based estimates, after which it turned into a sink of anthropogenic CO₂." Between the 1980s and 2000s, the strength of the global land sink grew from a value of 0.3 Pg C per year to 1.1 Pg C per year, suggesting the terrestrial biosphere has begun to "flex its muscles," likely in response to the aerial fertilization and transpiration-reducing effects of the ongoing rise in the air's CO₂ content. Others have challenged these findings, suggesting the world's oceans and terrestrial ecosystems may be gradually losing their ability to sequester CO₂ emissions (Canadell *et al.*, 2007; Le Quere *et al.*, 2007; Schuster and Watson, 2007).

Le Quere *et al.* (2009), for example, developed "a global CO₂ budget for each year during 1959–2008 and analyzed the underlying drivers of each component." In this undertaking, they say "the global increase in atmospheric CO₂ was determined directly from measurements, CO₂ emissions from fossil fuel combustion were estimated on the basis of countries' energy statistics, [while] CO₂ emissions from land-use change were estimated using deforestation and other land-use data, fire observations from space, and assumptions on the carbon density of vegetation and soils and the fate of carbon." For the time evolution of the land and ocean CO₂ sinks, they used "state-of-the-art models on which [they] imposed the observed meteorological conditions of the past few decades."

Le Quere *et al.* reported, "between 1959 and 2008, 43% of each year's CO₂ emissions remained in the atmosphere on average" and "the rest was absorbed by carbon sinks on land and in the oceans." They write, "in the past 50 years, the fraction of CO₂ emissions that remains in the atmosphere each year has likely increased, from about 40% to 45%," stating "models suggest that this trend was caused by a decrease in the uptake of CO₂ by the carbon sinks in response to climate change and variability."

Although their findings can be interpreted as indicating the uptake rate of anthropogenic CO₂ by the oceans, land, or both may have decreased with time—as they and others have suggested—they temper this conclusion with the caveat that "changes

in the CO₂ sinks are highly uncertain." It should be noted that the time evolution or temporal histories of the anthropogenic CO₂ sinks in Le Quere *et al.*'s analysis were obtained from models; they themselves admit "sink processes not considered in current models may be contributing to the observed changes" and these "sink processes" would be doing so in unknown ways not included in their calculations. In addition, the work of Khatiwala *et al.* (2009), which covers a longer span of time, reveals the existence of multidecadal variability that in a short half-century context could be interpreted as a trend, but in a much longer two-and-a-half century timeframe is readily recognized as an oscillatory variation about an essentially constant mean.

Knorr (2009) also covered a much longer time-span than Le Quere *et al.*, utilizing data on CO₂ emissions arising from fossil-fuel use, cement production, and changes in land use, as well as atmospheric CO₂ concentrations measured at Mauna Loa and the South Pole and those derived from Law Dome and Siple ice-core data, together with their associated uncertainties, to construct a history since 1850 of the airborne fraction of anthropogenic CO₂. The U.K. researcher reports, "despite the predictions of coupled climate-carbon cycle models, no trend in the airborne fraction can be found." He writes in the concluding section of his study, "the hypothesis of a recent or secular trend in the AF cannot be supported on the basis of the available data and its accuracy," indicating not only has the global ocean been increasing its uptake of anthropogenic carbon in such a way as to "keep up" with the rate at which the air's CO₂ content has risen—as has been demonstrated by Khatiwala *et al.* (2009)—so also have Earth's terrestrial ecosystems been "keeping up" in this regard.

Gloor *et al.* (2010) note Canadell *et al.* (2007) and Raupach *et al.* (2008) claimed to have detected a long-term increasing trend in the airborne fraction that they interpret as being indicative of "a decreasing trend in the efficiency of the ocean and land carbon sinks." Noting Knorr (2009) had already challenged Canadell *et al.* and Raupach *et al.* with respect to their detection of a positive AF trend, "arguing that given the noise in the data, the trend is not detectable," Gloor *et al.* (2010) proceeded to challenge the second claim of Canadell *et al.* and Raupach *et al.*; i.e., their contention that a positive AF trend is indicative of decreasing planetary carbon sink efficiency, by investigating "the question of what controls trends

and decadal scale variations in CO₂ airborne fraction using simple linear models describing the evolution of an atmospheric perturbation in CO₂.”

The three researchers first determined there is no one-to-one association between positive trends in CO₂ flux to the atmosphere due to fossil fuel emissions and changes in land use and negative trends in Earth’s carbon sink efficiency. Secondly, they found that in order to detect trends in sink efficiencies from the time course of fossil fuel-derived CO₂ emissions and temporal changes in land use, “it is necessary to disentangle the spin-up time and fossil fuel growth rate variation signatures in the airborne fraction from signatures due to other causes.” When they make the pertinent calculations for fossil-fuel and land-use changes, they say they “do indeed find a positive trend in the residuals,” but they argue this trend “is not statistically significant after correcting for known events such as the temporal distribution of the extrinsic forcings and likely omissions in the emissions (particularly from land-use change),” further noting their analysis suggests “trends in airborne fraction are not a very good diagnostic to detect changes in carbon sink efficiency because variations in the signal are complex and the signal-to-noise ratio is small.”

Thus, Gloor *et al.* conclude “atmospheric data, if analyzed adequately, do not yet reveal a statistically significant signal.” They further note, “although approximately one-half of total CO₂ emissions is at present taken up by combined land and ocean carbon reservoirs (Schimel *et al.*, 2001),” coupled climate/carbon-cycle models “predict a decline in future carbon uptake by these reservoirs, resulting in a positive carbon-climate feedback.”

In an effort to shed more light on the subject, Ballantyne *et al.* (2012) used “global-scale atmospheric CO₂ measurements, CO₂ emission inventories and their full range of uncertainties to calculate changes in global CO₂ sources and sinks during the past fifty years.” The five U.S. scientists say their mass balance analysis shows “net global carbon uptake has increased significantly by about 0.05 billion tonnes of carbon per year and that global carbon uptake doubled, from 2.4 ± 0.8 to 5.0 ± 0.9 billion tonnes per year, between 1960 and 2010.” Ballantyne *et al.* conclude, “although present predictions indicate diminished C uptake by the land and oceans in the coming century, with potentially serious consequences for the global climate, as of 2010 there is no empirical evidence that C uptake has started to diminish on the global scale.”

Other research lends confidence to the idea that the carbon-sequestering strength of the land and ocean will continue in the future, even in the face of rising temperatures. Allen *et al.* (1999) analyzed sediment cores from a lake in Italy and the Mediterranean Sea, determining that over the past 102,000 years, the warm period of the Holocene produced organic carbon content in vegetation more than double that observed for any other period in this historic record. Similarly, Velichko *et al.* (1999) reconstructed carbon storage in vegetation in Northern Eurasia, determining plant life there was more productive and efficient in sequestering carbon at higher, as opposed to lower, air temperatures. Vegetative carbon storage during the Holocene Optimum, which occurred about 6,000 years ago, was calculated to be 120 percent greater than present-day carbon sequestration in this region.

In assessing the ability of Earth’s vegetation to sequester carbon in the future, it is also important to consider the findings of Luz *et al.* (1999), who estimated the biospheric productivity of the planet as a whole is currently at its highest point in the past 82,000 years, as is the atmospheric CO₂ concentration. Xiao *et al.* (1998) used a process-based ecosystem model to compute global net ecosystem production from 1990 to 2100 based on three scenarios of atmospheric CO₂ and temperature change. In all cases where these parameters increased together, they reported positive increases in global net ecosystem productivity.

It should be clear from the observational data that Earth’s biosphere is exerting a powerful brake on the rate of rise of the air’s CO₂ content, such that the large increases in anthropogenic CO₂ emissions of the past two decades have not resulted in any increase in the rate of CO₂ accumulation in the atmosphere. The IPCC has yet to acknowledge the existence and sign of this negative feedback, choosing to rely on projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. Those models “consistently estimate a positive carbon cycle feedback, i.e. reduced natural sinks or increased natural CO₂ sources in response to future climate change.” The models further find “in particular, carbon sinks in tropical land ecosystems are vulnerable to climate change” (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

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2.6.2 Carbonyl Sulfide

Idso (1990) suggested the volatilization of reduced sulfur gases from Earth's soils may be just as important as dimethyl sulfide (DMS) emissions from the world's oceans in enhancing cloud albedo, cooling the planet, and providing a natural brake on the tendency for anthropogenically enhanced greenhouse gases to drive global warming. (See Dimethylsulfide, Section 2.6.2.1.1.)

Experiments have shown soil DMS emissions to be positively correlated with soil organic matter content, and Idso noted additions of organic matter to soils tend to increase the amount of sulfur gases they emit. Because atmospheric CO₂ enrichment augments plant growth and, as a result, vegetative inputs of organic matter to Earth's soils, Idso hypothesized this phenomenon should produce an impetus for cooling, even in the absence of the surface warming that sets in motion the chain of events that produce the oceanic DMS-induced negative feedback cooling the planet.

Two years later, Idso (1992) expanded his work to include another biologically produced sulfur gas emitted from soils: carbonyl sulfide, a chemical compound with the formula OCS, but often written as COS. He noted COS is likely to be emitted in increasing quantities as Earth's vegetation responds to the ongoing rise in the air's CO₂ content. While COS is relatively inert in the troposphere, it eventually makes its way into the stratosphere, where it is transformed into solar-radiation-reflecting sulfate aerosol particles. He concluded the CO₂-induced augmentation of soil COS emissions constitutes a mechanism that can cool the planet's surface in the absence of an impetus for warming, without producing additional clouds or making them any brighter.

Researchers subsequently have learned the COS-induced cooling mechanism also operates at sea, just as the DMS-induced cooling mechanism does, and it too possesses a warming-induced component in addition to its CO₂-induced component. Andreae and Ferek (1992) demonstrated ocean-surface COS concentrations are highly correlated with surface-water primary productivity. So strong is this correlation that Erickson and Eaton (1993) developed an empirical model for computing ocean-surface COS concentrations based solely on surface-water chlorophyll concentrations and values of incoming solar radiation.

Researchers also have learned an even greater portion of naturally produced COS is created in the atmosphere, where carbon disulfide and dimethyl sulfide—also largely of oceanic origin (Aydin *et al.*, 2002)—undergo photochemical oxidation (Khalil and Rasmussen, 1984; Barnes *et al.*, 1994). The majority of the tropospheric burden of COS is ultimately dependent upon photosynthetic activity occurring near the surface of the world's oceans.

The tropospheric COS concentration has risen by approximately 30 percent since the 1600s, from a mean value of 373 ppt over the period 1616–1694 to something on the order of 485 ppt today. Aydin *et al.* (2002) have noted only a quarter of this increase can be attributed to anthropogenic sources. The rest of the observed COS increase must have had a natural origin, a large portion of which must have been derived from the products and byproducts of marine photosynthetic activity, which must have increased substantially over the past three centuries. The increases in atmospheric CO₂ concentration and temperature experienced over this period were likely driving forces for the increase in tropospheric COS concentration and its subsequent transport to the stratosphere, where it could exert a cooling influence on the Earth. This chain of events may have kept the warming of the globe considerably below what it might otherwise have been.

Another aspect of this multifaceted global “biothermostat” was revealed in a laboratory study of samples of the lichen *Ramalina menziesii* collected from an open oak woodland in central California, USA by Kuhn and Kesselmeier (2000). When the lichens were optimally hydrated, the researchers found, they absorbed COS from the air at a rate that gradually doubled as air temperature rose from approximately 3° to 25°C, whereupon their rate of COS absorption began a precipitous decline that led to zero COS absorption at 35°C.

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Most terrestrial plants thrive in temperatures much warmer than 3°C; as their surroundings warm and they grow better, they extract more COS from the atmosphere, promoting more warming and growing better still. But above a certain temperature warming becomes detrimental to plants, and they begin to reduce their rates of COS absorption, resulting in cooling. The carbonic anhydrase enzyme that governs the uptake of COS in lichens also controls it in all higher plants, algae, and soil organisms, suggesting this thermoregulatory function of the biosphere likely operates across the globe.

Sandoval-Soto *et al.* (2012) reiterated the importance of COS in the atmosphere, noting, “aside from sulfur dioxide, carbonyl sulfide (COS) is the most abundant sulfur gas in the atmosphere with relative constant mixing ratios of 450–500 ppt and a lifetime of more than two years.” They point out “COS can be transported up into the stratosphere,” where it “may serve as a source of sulfur to the stratospheric aerosol layer by conversion to sulfuric acid (Junge *et al.*, 1961; Crutzen, 1976),” thereby contributing to the scattering of incoming solar radiation back to space and exerting a cooling influence on Earth. In addition, they note terrestrial vegetation “acts as the main sink for this trace gas,” and it is “heavily underestimated” in this regard, citing the work of Notholt *et al.* (2003), Mu *et al.* (2004), Sandoval-Soto *et al.* (2005), Campbell *et al.* (2008), Suntharalingam *et al.* (2008), and Van Diest and Kesselmeier (2008).

Further exploring the relationship between increasing atmospheric CO₂ and COS, Sandoval-Soto *et al.* grew three- to four-year-old holm oak (*Quercus ilex* L.) and European beech (*Fagus sylvatica* L.) trees in greenhouse chambers from March 1998 to February 2000 at atmospheric CO₂ concentrations of either 350 or 800 ppm, measuring a number of plant physiological properties and processes. In the case of holm oak, the five researchers report there was “a decrease of the COS uptake capacity induced by high CO₂ levels under long-term conditions,” and their data for beech support “a similar interpretation.” They conclude increasing levels of atmospheric CO₂ may have had a tempering effect on Earth’s rate of warming during the development of the planet’s Current Warm Period, and that cooling influence could increase in the future.

This multifaceted phenomenon is clearly complex, with different biological entities affecting atmospheric COS concentrations simultaneously but

in different ways, while periodically reversing directions in response to changing temperatures. There is obviously much to be learned about the plant physiological mechanisms that may be involved. Until the COS cycle is fully understood and incorporated into the climate models, it cannot be known just how much of the warming experienced during the twentieth century can be attributed to anthropogenic sources.

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2.6.3 Diffuse Light

Another negative feedback phenomenon is diffuse light. It operates through a chain of five linkages triggered by the incremental enhancement of the atmosphere's greenhouse effect produced by an increase in the air's CO₂ content.

The first linkage is the proven propensity for higher levels of atmospheric CO₂ to enhance vegetative productivity, a powerful negative feedback mechanism. Greater CO₂-enhanced photosynthetic rates, for example, enable plants to remove considerably more CO₂ from the air than they do under current conditions, while CO₂-induced increases in plant water use efficiency allow plants to grow where it was previously too dry for them. This establishes a potential for more CO₂ to be removed from the atmosphere by increasing the abundance of

Earth's plants and increasing their robustness (see Carbon Sequestration, Section 2.6.1, this volume).

The second linkage of the feedback loop is the ability of plants to emit gases to the atmosphere that are ultimately converted into “biosols”—aerosols that owe their existence to the biological activities of Earth's vegetation, many of which function as cloud condensation nuclei. Since the existence of these atmospheric particles is dependent upon the physiological activities of plants and their associated soil biota, the CO₂-induced presence of more, and more-highly-productive, plants will lead to the production of more of these cloud-mediating particles, which can then result in more clouds that reflect sunlight and act to cool the planet.

The third linkage is the observed propensity for increases in aerosols and cloud particles to enhance the amount of diffuse solar radiation reaching Earth's surface. The fourth linkage is the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies. The fifth linkage is the tendency for less internal canopy shading to enhance whole-canopy photosynthesis, which produces the end result: a greater biological extraction of CO₂ from the air and the subsequent sequestration of its carbon.

Roderick *et al.* (2001) provide a good estimate of the significance of this process based on a unique “natural experiment,” a technique used extensively by Idso (1998) to evaluate the climatic sensitivity of the planet. Roderick and his colleagues considered the volcanic eruption of Mt. Pinatubo in June 1991, which ejected enough gases and fine materials into the atmosphere to produce sufficient aerosol particles to greatly increase the diffuse component of the solar radiation reaching the surface of Earth from that point in time through much of 1993, while only slightly reducing the receipt of total solar radiation.

Based on a set of lengthy calculations, they conclude the Mt. Pinatubo eruption may have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial vegetation in the year following the eruption, which would have reduced the ongoing rise in the air's CO₂ concentration that year by about 1.2 ppm. The reduction they calculated is approximately the magnitude of the change in CO₂ concentration actually observed (Sarmiento, 1993).

Bolstering the attribution of this change to diffuse light, Roderick *et al.* note the CO₂ reduction was coincident with an El Niño event, whereas “previous and subsequent such events have been associated with increases in atmospheric CO₂.” Moreover, the

observed reduction in *total* solar radiation received at Earth's surface during this period would have had a tendency to reduce the amount of photosynthetically active radiation, would have had a tendency to cause the air's CO₂ content to rise by lessening global photosynthetic activity.

Further support for the new negative feedback phenomenon came in 2002, when a team of 33 researchers published the results of a comprehensive study (Law *et al.*, 2002) that compared seasonal and annual values of CO₂ and water vapor exchange across sites in forests, grasslands, crops, and tundra—part of an international network called FLUXNET—investigating the responses of these exchanges to variations in a number of environmental factors, including direct and diffuse solar radiation. The researchers report “net carbon uptake (net ecosystem exchange, the net of photosynthesis and respiration) was greater under diffuse than under direct radiation conditions.” In discussing this finding, which is the centerpiece of the negative feedback phenomenon described in this section, they note “cloud-cover results in a greater proportion of diffuse radiation and constitutes a higher fraction of light penetrating to lower depths of the canopy (Oechel and Lawrence, 1985).” They also report “Goulden *et al.* (1997), Fitzjarrald *et al.* (1995), and Sakai *et al.* (1996) showed that net carbon uptake was consistently higher during cloudy periods in a boreal coniferous forest than during sunny periods with the same PPFD [photosynthetic photon flux density].” They also write, “Hollinger *et al.* (1994) found that daily net CO₂ uptake was greater on cloudy days, even though total PPFD was 21–45 percent lower on cloudy days than on clear days.”

Gu *et al.* (2003) “used two independent and direct methods to examine the photosynthetic response of a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W) to changes in diffuse radiation caused by Mount Pinatubo's volcanic aerosols.” In the eruption year of 1991, they found, “around noontime in the mid-growing season, the gross photosynthetic rate under the perturbed cloudless solar radiation regime was 23, 8, and 4 percent higher than that under the normal cloudless solar radiation regime in 1992, 1993, and 1994, respectively,” and “integrated over a day, the enhancement for canopy gross photosynthesis by the volcanic aerosols was 21 percent in 1992, 6 percent in 1993 and 3 percent in 1994.” Gu *et al.* write, “because of substantial increases in diffuse radiation world-wide after the

eruption and strong positive effects of diffuse radiation for a variety of vegetation types, it is likely that our findings at Harvard Forest represent a global phenomenon.”

The diffuse-light-induced photosynthetic enhancement observed by Gu *et al.* was caused by volcanic aerosols acting under cloudless conditions. That distinguishes this phenomenon from a closely related one also described by Gu *et al.*—the propensity for the extra diffuse light created by increased cloud cover to enhance photosynthesis even though the total flux of solar radiation received at Earth's surface may be reduced under such conditions. Gu *et al.* note, “Harvard Forest photosynthesis also increases with cloud cover, with a peak at about 50 percent cloud cover.”

The work reviewed above focuses on the enhanced atmospheric aerosol concentration caused by a singular significant event: a massive volcanic eruption. Niyogi *et al.* (2004) asked a more general question: “Can we detect the effect of relatively routine aerosol variability on field measurements of CO₂ fluxes, and if so, how does the variability in aerosol loading affect CO₂ fluxes over different landscapes?”

The group of 16 researchers used CO₂ flux data from the AmeriFlux network (Baldocchi *et al.*, 2001) together with cloud-free aerosol optical depth data from the NASA Robotic Network (AERONET; Holben *et al.*, 2001) to assess the effect of aerosol loading on the net assimilation of CO₂ by three types of vegetation: trees (broadleaf deciduous forest and mixed forest), crops (winter wheat, soybeans, and corn), and grasslands.

Their work revealed an aerosol-induced increase in diffuse radiative-flux fraction [DRF = ratio of diffuse (R_d) to total or global (R_g) solar irradiance] increased the net CO₂ assimilation of trees and crops, making them larger carbon sinks, but decreased the net CO₂ assimilation of grasslands, making them smaller carbon sinks. For a summer midrange R_g flux of 500 W m⁻², going from the set of all DRF values between 0.0 and 0.4 to the set of all DRF values between 0.6 and 1.0 resulted in an approximate 50 percent increase in net CO₂ assimilation by a broadleaf deciduous forest located in Tennessee, USA. Averaged over the entire daylight period, the shift from the lower to the higher set of DRF values “enhances photosynthetic fluxes by about 30 percent at this study site.” Similar results were obtained for the mixed forest and the conglomerate of crops

studied. Niyogi *et al.* conclude natural variability among commonly present aerosols can “routinely influence surface irradiance and hence the terrestrial CO₂ flux and regional carbon cycle.” For these types of land cover (forests and agricultural crops), that influence significantly increases the assimilation of CO₂ from the atmosphere. In the case of grasslands, Niyogi *et al.* found the opposite effect, with greater aerosol loading of the atmosphere leading to less CO₂ assimilation. The researchers suggest this result was most likely due to grasslands’ significantly different canopy architecture.

With respect to the planet as a whole, the net effect of diffuse light processes is decidedly positive, as Earth’s trees are key in carbon sequestration. Post *et al.* (1990) note woody plants account for approximately 75 percent of terrestrial photosynthesis, which represents about 90 percent of all photosynthesis (Sellers and McCarthy, 1990).

Moreover, much of the commonly present aerosol burden of the atmosphere is plant-derived. Woody plants are themselves responsible for emitting to the air that which ultimately enhances photosynthesis. Earth’s trees alter the atmospheric environment in a way that directly enhances their growth. And as humans release more CO₂ into the atmosphere, the globe’s woody plants respond to its aerial fertilization effect, becoming increasingly productive, leading to even more plant-derived aerosols being released to the atmosphere, further stimulating this positive feedback cycle. These effects are not adequately incorporated into the climate models.

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2.6.4 Iodocompounds

The climatic significance of iodinated compounds, or iodocompounds, was initially described in *Nature* by O'Dowd *et al.* (2002). As related by Kolb (2002) in an accompanying perspective on their work, the 10-member research team discovered “a previously unrecognized source of aerosol particles” by unraveling “a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides.”

O'Dowd *et al.* used a smog chamber operated under coastal atmospheric conditions to demonstrate, as they report, “new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae.” They also demonstrated, using aerosol formation models, that concentrations of condensable iodine-containing vapors over the open ocean “are sufficient to influence marine particle formation.”

The aerosol particles O'Dowd *et al.* discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet (a negative feedback). With respect to the negative feedback nature of this phenomenon, O'Dowd *et al.* cite the work of Laturnus *et al.* (2000), who demonstrated emissions of iodocarbons from marine biota “can increase by up to 5 times as a result of changes in environmental conditions associated with global change.” Therefore, O'Dowd *et al.* write, “increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20–60 percent.” Furthermore, they note, “changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global radiative forcing similar in magnitude, but opposite in sign, to

the forcing induced by greenhouse gases.”

Four years later, Smythe-Wright *et al.* (2006) measured trace gas and pigment concentrations in seawater, while identifying and enumerating picophytoprokarayotes during two ship cruises in the Atlantic Ocean and one in the Indian Ocean, where they focused “on methyl iodide production and the importance of a biologically related source.” They encountered methyl iodide concentrations as great as 45 pmol per liter in the top 150 meters of the oceanic water column that correlated well with the abundance of *Prochlorococcus*, which they reported “can account for >80 percent of the variability in the methyl iodide concentrations.” They further state they “have confirmed the release of methyl iodide by this species in laboratory culture experiments.”

Extrapolating their findings to the globe as a whole, the six researchers “estimate the global ocean flux of iodine [I] to the marine boundary layer from this single source to be 5.3×10^{11} g I year⁻¹,” which they state “is a large fraction of the total estimated global flux of iodine (10^{11} - 10^{12} g I year⁻¹).” Smythe-Wright *et al.* point out volatile iodinated compounds “play a part in the formation of new particles and cloud condensation nuclei (CCN),” and “an increase in the production of iodocompounds and the subsequent production of CCN would potentially result in a net cooling of the Earth system and hence in a negative climate feedback mechanism, mitigating global warming.” They suggest “as ocean waters become warmer and more stratified, nutrient concentrations will fall and there will likely be a regime shift away from microalgae toward *Prochlorococcus*,” such that “colonization within the <50° latitude band will result in a ~15 percent increase in the release of iodine to the atmosphere,” with consequent “important implications for global climate change.”

As part of the Third Pelagic Ecosystem CO₂ Enrichment Study, Wingenter *et al.* (2007) investigated the effects of atmospheric CO₂ enrichment on marine microorganisms in nine marine mesocosms maintained within two-meter-diameter polyethylene bags submerged to a depth of 10 meters in a fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espesrend, Norway. Three of these mesocosms were maintained at ambient levels of CO₂ (~375 ppm or base CO₂), three were maintained at levels expected to prevail at the end of the current century (760 ppm or 2xCO₂), and three were maintained at levels

predicted for the middle of the next century (1150 ppm or $3\times\text{CO}_2$). During the 25 days of this experiment, the researchers followed the development and subsequent decline of an induced bloom of the coccolithophorid *Emiliana huxleyi*, carefully measuring several physical, chemical, and biological parameters along the way. This work revealed iodo-carbon chloriodomethane (CH_2CIH) concentrations peaked about six to 10 days after the coccolithophorid's chlorophyll-a maximum, and the peak estimated abundance was 46 percent higher in the $2\times\text{CO}_2$ mesocosms and 131 percent higher in the $3\times\text{CO}_2$ mesocosms.

The international team of scientists concludes the differences in the CH_2CIH concentrations “may be viewed as a result of changes to the ecosystems as a whole brought on by the CO_2 perturbations.” Because emissions of various iodocarbons have been found to lead to an enhancement of cloud condensation nuclei in the marine atmosphere, as demonstrated by O'Dowd *et al.* (2002) and Jimenez *et al.* (2003), the CO_2 -induced stimulation of marine emissions of these substances provides a natural brake on the tendency for global warming to occur as a consequence of any forcing, as iodocarbons lead to the creation of more highly reflective clouds over greater areas of the world's oceans. As Wingenter *et al.* conclude, the processes described above “may help contribute to the homeostasis of the planet.”

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2.6.5 Stratospheric Perturbations

Few researchers have examined the influence of the stratosphere on global climate, yet several studies indicate this layer of the atmosphere has a significant impact on various climate parameters.

In an early study of the subject, Hartley *et al.* (1998) utilized meteorological data for the winter of 1992–93 to study a broad range of stratospheric polar vortex distortions for possible impacts on meteorological events in the troposphere. As they describe it, the results of their study “clearly indicate that stratospheric processes induce significant anomalies in dynamical fields at the tropopause.”

Previously, although atmospheric processes of tropospheric origin were known to have the ability to perturb the stratosphere, feedback in the opposite direction was assumed to be negligible. The results of Hartley *et al.*'s study, however, demonstrate this assumption was incorrect, leading them to suggest a more realistic representation of the stratosphere may be required to enable general circulation models (GCMs) of the atmosphere to properly simulate the troposphere.

This shortcoming of current climate models may be critical, for scientists have long suspected the upper atmosphere may amplify the effects of a number of solar phenomena. The work of Hartley *et al.* suggests the amplified perturbations of these phenomena may be propagated downward to the troposphere, where they could significantly impact Earth's climate.

Initial evidence that such perturbations may indeed influencing climate near Earth's surface is seen in the work of Thompson and Solomon (2002), who explored a number of different data sets in Antarctica to define the nature of climate change in Antarctica since 1969 and determine the reasons for the observed changes. The two researchers found “at the surface, the Antarctic Peninsula has warmed by several [degrees C] over the past several decades,

while the interior of the Antarctic continent has exhibited weak cooling.” In addition, they note, “ice shelves have retreated over the peninsula and sea-ice extent has decreased over the Bellingshausen Sea, while sea-ice concentration has increased and the length of the sea-ice season has increased over much of eastern Antarctica and the Ross Sea.” With respect to atmospheric circulation, they write there was “a systematic bias toward the high-index polarity of the SAM,” or Southern Hemispheric Annular Mode, such that the ring of westerly winds encircling Antarctica recently has been spending more time in its strong-wind phase.

The heightened strength and persistence of the SAM can explain most of the cooling experienced over the bulk of Antarctica over the past several decades as well as much of the warming of the Antarctica Peninsula, as the latter location experiences fewer cold-air outbreaks under such conditions while simultaneously receiving increased advective warmth from the Southern Ocean. As for what caused the strengthening of the SAM, Thompson and Solomon speculate it is related to “recent trends in the lower stratospheric polar vortex, which are due largely to photochemical ozone losses.”

Similar findings were reported in a contemporaneous study conducted by Kwok and Comiso (2002), who also report the SAM index shifted towards more positive values (0.22/decade) over the 17-year period 1982–1998, while noting a positive polarity of the SAM index “is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau.” Simultaneously, the SO index shifted in a negative direction, indicating “a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over much of the continent.” The authors report the positive trend in the coupled mode of variability of these two indices (0.3/decade) represents a “significant bias toward positive polarity,” which they describe as “remarkable.”

Kwok and Comiso note “the tropospheric SH annular mode has been shown to be related to changes in the lower stratosphere (Thompson and Wallace, 2000)” and “the high index polarity of the SH annular mode is associated with the trend toward a cooling and strengthening of the SH stratospheric polar vortex during the stratosphere’s relatively short active season in November, and ozone depletion,” much the same

theory put forth by Thompson and Solomon (2002).

Thejll *et al.* (2003) also demonstrated a link between stratospheric perturbations and tropospheric climate. They investigated various spatial and temporal relationships among several parameters, including the geomagnetic index (*Ap*), the NAO, stratospheric geopotential height, and sea level pressure. The three researchers report “significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000,” but “for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere.” By using “Monte Carlo simulations of the statistical procedures applied to suitable surrogate data,” they conclude these correlations are due to the existence of a “real physical link.” They also note in the 1973–2000 period only the winter season series are significantly correlated, which they said “is consistent with the notion that the solar-climate link works through the stratosphere.”

Thejll *et al.* suggest their findings may be explained in two different ways: either the influence of the Sun increased through time, reaching a strong enough level in the 1970s to make the correlations they studied become statistically significant, or the state of the atmosphere changed in the 1970s, becoming more sensitive to the solar influence than it had been. In either event, their findings strengthen the argument for solar-induced perturbations being propagated downward from the stratosphere to the troposphere (Hartley *et al.*, 1998; Carslaw *et al.*, 2002).

Ineson *et al.* (2011) modeled the effects from realistic solar UV (200–320 nm) irradiance changes between solar activity minima and maxima in the stratosphere and mesosphere, finding weaker westerly winds during the winters with a less active Sun that may correspond with cold winters in Northern Europe and the United States and mild winters over Southern Europe and Canada, as observed in recent years. The observational analyses by Hood *et al.* (2013) added insight into the specific regional patterns of near-surface responses that more than likely originate from the solar UV forcing of ozone and related wind-thermal fields in the stratosphere.

Kristjansson *et al.*’s (2002) observation that “low clouds appear to be significantly inversely correlated with solar irradiance” led them to suggest a possible physical mechanism linked to the stratosphere that could explain this phenomenon. This mechanism, in

their words, “acts through UV [ultraviolet radiation] in the stratosphere affecting tropospheric planetary waves and hence the subtropical highs, modulated by an interaction between sea surface temperature [SST] and lower tropospheric static stability,” which “relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics.” Based on experimentally determined values of factors that enter into this process, they obtained a value for the amplitude of the variation in low cloud cover over a solar cycle that “is very close to the observed amplitude.”

Tiwari *et al.* (2005) report the Asian SouthWest Monsoon (SWM) intensity on a centennial scale “is governed by variation in TSI,” yet “variations in TSI (~0.2%) seem to be too small to perturb the SWM, unless assisted by some internal amplification mechanism with positive feedback.” They discuss a possible mechanism that “involves heating of the Earth’s stratosphere by increased absorption of solar ultraviolet (UV) radiation by ozone during periods of enhanced solar activity (Schneider, 2005).” They posit more UV reception leads to more ozone production in the stratosphere, which leads to more heat being transferred to the troposphere, which leads to enhanced evaporation from the oceans, which enhances monsoon winds and precipitation.

de Jager (2005) reviewed what is known about the role of the Sun in orchestrating climate change over the course of the Holocene, including changes that occurred during the twentieth century. Commenting on the direct effects of solar irradiance variations, de Jager reports “the fraction of the solar irradiance that directly reaches the Earth’s troposphere is emitted by the solar photosphere [and] does not significantly vary.” The variable part of this energy flux, he states, is emitted by chromospheric parts of centers of solar activity, and “it only directly influences the higher, stratospheric terrestrial layers,” which “can only influence the troposphere by some form of stratosphere-troposphere coupling.”

Solomon *et al.* (2010) point out “the trend in global surface temperatures has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases (CO₂, CH₄, halocarbons, and N₂O), raising questions regarding the understanding of forced climate change, its drivers, the parameters that define natural internal variability, and how fully these terms are represented in climate models.” They used observations of stratospheric water vapor concentration obtained over the period 1980–2008,

together with detailed radiative transfer and modeling information, to calculate the global climatic impact of water vapor and compare it with trends in mean global near-surface air temperature observed over the same time period.

The seven scientists found stratospheric water vapor concentrations decreased by about 10 percent after the year 2000, and their analysis indicates this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25 percent compared to what would have been expected on the basis of climate model calculations due to measured increases in carbon dioxide and other greenhouse gases over the same period. In addition, they found, “more limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% [above what it would have been without the stratospheric water vapor increase].”

Solomon *et al.* conclude it is “not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability.” In either case, their findings describe a phenomenon not included in prior analyses of global climate change. They also indicate current climate models do not “completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures, or the impact of aerosol heating on water input to the stratosphere.”

In light of Solomon *et al.*’s findings, their identification of what current climate models do not but should do, and the questions they say are raised by the flatlining of mean global near-surface air temperature since the late 1990s, it is premature to conclude current state-of-the-art models know enough to correctly simulate the intricate workings of Earth’s climate regulatory system. The other studies cited in this section also indicate much research remains to be conducted in order to more correctly characterize and quantify the stratosphere’s influence on global climate.

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2.6.6 Volcanism

Volcanic forcings are not a function of human activities. Their impact on climate and human history is well documented and takes many forms, especially with major events with a global impact such as Tambora, Laki, and more recently Pinatubo.

In general, large volcanic eruptions eject particulate and aerosol materials into the stratosphere. These aerosols, primarily sulfate type, increase the

albedo of the planet, which means less solar radiation coming in. The result is a cooling of the lower troposphere and surface. Generally, the greater the eruption, the stronger this effect will be and the longer it will last. Smaller volcanic eruptions confined to the troposphere have little effect on the climate, as the troposphere is more efficient in scavenging out the relatively large particulates. Still, much remains to be learned about this external forcing of the climate, and as the research highlighted below indicates, not all scientists are in agreement regarding the long-term importance of this forcing on climate.

Briffa and Jones (1998) used tree-ring wood density data from more than 380 boreal forest locations in the Northern Hemisphere as surrogates for summertime temperatures, looking for effects of large volcanic eruptions on climate since 1400 AD. This exercise indicated major volcanic eruptions seemed to produce significant Northern Hemispheric cooling the year after their occurrence, with the largest of the temperature declines they detected estimated to be 0.81°C in 1601, the year following the eruption of Huaynaputina in Peru.

Of the six centuries examined, the seventeenth century experienced the greatest number (six) of climatically significant eruptions. Strong temperature anomalies suggested there were three other major volcanic eruptions during the late seventeenth century not reported in historical accounts. The researchers also found every Northern Hemispheric temperature departure of 0.3°C or more since 1400 (19 total events) followed a confirmed major volcanic eruption. This study thus suggests there is a strong link between volcanic activity and large-scale temperature variability, and it may help to explain the cool temperatures of the Little Ice Age by illustrating how closely spaced multiple eruptions could reduce hemispheric temperatures on decadal and multidecadal time scales, as well as how a lack of such eruptions could result in periods of warmer global temperatures.

Building on this perceived relationship, Hyde and Crowley (2000) analyzed statistical properties of climatically significant volcanic eruptions over the past 600 years in an effort to estimate the probability of future eruptions. They conclude there was a 35 to 40 percent probability of a volcanic eruption occurring with the capability of producing a radiative perturbation of -1 W m⁻² or larger in the following 10 years. Such an eruption was estimated to produce a

0.1°C to 0.15°C cooling over a two- to three-year period, while the probability of a larger Mt. Pinatubo-scale eruption with a radiative perturbation of -3 W m^{-2} was estimated to be 15 to 25 percent. The two scientists note if a major volcanic eruption were to occur in the next decade (which seems a reasonable possibility), it could “mask the CO₂ effect and complicate discussions on a greenhouse gas protocol.”

Sadler and Grattan (1999) examined a number of issues related to the linking of volcanic activity with spatial and temporal events in climatic, historical, and palaeoecological records. Although volcanoes can have a significant effect on proximal climates, they conclude, their global impact is less well understood. The message of their paper is thus one of caution in drawing conclusions about climate change and its connection to volcanic explosions. They report, for example, “a run of bad summers, an increase in sea ice off America, narrow rings in dendrochronological sequences, and neoglaciations can all be linked to temporally convenient climate forcing by volcanic aerosols.” In addition, they note “speculation as to the likely effect of these eruptions on fauna and flora and human societies may involve further supposition.” They also note “the role of precursor climatic and/or environmental conditions is frequently overlooked” and “it is valid to question whether the relationships established are fortuitous rather than dependent.” As one of the scientists they quote has aptly phrased it, “an eruption here, a destruction there, a plague somewhere else—all are too easily linked in hasty surmise.”

Yet another indication the climatic effects of volcanic eruptions may not be well established is provided by Douglass and Knox (2005), who “determined the volcano climate sensitivity and response time for the Mount Pinatubo eruption, using observational measurements of the temperature anomalies of the lower troposphere, measurements of the long wave outgoing radiation, and the aerosol optical density.” Their analysis revealed “a short atmospheric response time, of the order of several months, leaving no volcano effect in the pipeline, and a negative feedback to its forcing.”

One of the issues raised by these results, according to Douglass and Knox, concerns “the origin of the required negative feedback.” With respect to this question, they report “negative feedback processes have been proposed involving cirrus clouds (Lindzen *et al.*, 2001)” and “Sassen (1992) reports that cirrus clouds were produced during the Mt.

Pinatubo event.” In addition, they note the adaptive infrared iris concept of Lindzen *et al.* (2001) “yields a negative feedback factor of -1.1, which is well within the error estimate of the feedback found by us.” They also observe the short intrinsic response time they derived (6.8 ± 1.5 months) “confirms suggestions of Lindzen and Giannitsis (1998, 2002) that a low sensitivity and small lifetime are more appropriate” than the “long response times and positive feedback” characteristic of the reigning climate paradigm.

Tuffen (2010) writes “there is growing evidence that past changes in the thickness of ice covering volcanoes have affected their eruptive activity.” He further states “the rate of volcanic activity in Iceland accelerated by a factor of 30–50 following the last deglaciation at approximately 12 ka (MacLennan *et al.*, 2002)” and “analyses of local and global eruption databases have identified a statistically significant correlation between periods of climatic warming associated with recession of ice and an increase in the frequency of eruptions (Jellinek *et al.*, 2004; Nowell *et al.*, 2006; Huybers and Langmuir, 2009).” Thus he asks the next logical question: “Will the current ice recession provoke increased volcanic activity and lead to increased exposure to volcanic hazards?”

Tuffen—a researcher at the Lancaster Environment Centre of Lancaster University in the United Kingdom—“analyze[d] our current knowledge of how ice thickness variations influence volcanism” and “identif[ied] several unresolved issues that currently prevent quantitative assessment of whether activity is likely to accelerate in the coming century.” He found “ice unloading may encourage more explosive eruptions” but “melting of ice and snow may decrease the likelihood and magnitude of meltwater floods.” On the other hand, he writes, there is “uncertainty about the time scale of volcanic responses to ice unloading,” “poor constraint on how ice bodies on volcanoes will respond to twenty-first century climate change,” and “lack of data on how past changes in ice thickness have affected the style of volcanic eruptions and associated hazards.” He also notes “the sensitivity of volcanoes to small changes in ice thickness or to recession of small glaciers on their flanks is unknown,” “it is not known how localized ice withdrawal from stratovolcanoes [tall, conical volcanoes with many layers (strata) of hardened lava, tephra, and volcanic ash] will affect shallow crustal magma storage and eruption,” and “broader feedbacks between volcanism and climate change remain poorly understood.”

The U.K. researcher concludes by stating, “in

order to resolve these problems, both new data and improved models are required.” With respect to data, he adds, “existing databases of known volcanic eruptions need to be augmented by numerous detailed case studies of the Quaternary eruptive history of ice-covered volcanoes.” Regarding models, he notes, “improved physical models are required to test how magma generation, storage and eruption at stratovolcanoes are affected by stress perturbations related to the waxing and waning of small-volume ice bodies on what is commonly steep topography.” Finally, he states, “feedbacks between the mass balance of ice sheets and glaciers and volcanic activity need to be incorporated into future Earth-system models.”

Kravitz *et al.* (2011) focused on the ability of climate models to correctly represent volcanic aerosol forcing of climate. In June 2009, the Sarychev volcano in the Kamchatka Peninsula erupted explosively for a period of approximately five days. It injected 1.2 terragrams (Tg) of material into the atmosphere to an estimated height of as much as 16 km, nearly 10 miles. It was the second such eruption within a year. Taking advantage of this opportunity, Kravitz *et al.* studied measurements of the optical depth of the aerosol sulfates from the eruption and compared them with the projected output from a 20-member GCM ensemble, aiming to provide suggestions for improving the model’s capabilities. They used the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies Model-E, a coupled atmosphere-ocean GCM with fairly coarse resolution in the horizontal (4° by 5° lat/lon) and vertical (23 layers). The model contained levels up to 80 km, necessarily including the stratosphere.

The control model run consisted of a 20-member suite globally over the period 2007–2010. In this experiment, 1.5 Tg of volcanic material was injected into the atmosphere at a point near Sarychev in 2008 of the model year. The observed aerosol measurements came from ground-based LIDARS at six locations around the world as well as satellite-based measurements that profile the aerosol concentration using scattered sunlight (Optical Spectrograph and Infrared Imaging System (OSIRIS)).

The model did a reasonably good job spreading the volcanic material around the Northern Hemisphere, but there were some important discrepancies between the model and observations

(see Figure 2.6.6.1). The model transported the material too quickly into the tropics and too slowly into the high latitudes. The authors speculate this error may highlight the need to improve the model’s stratospheric circulation. The model also tended to remove aerosols too quickly from the atmosphere, especially in the high latitudes, which may have been a function of the model overestimating particulate size. As shown in Figure 2.6.6.1, the modeled peak aerosol values occur one month earlier than observed and then decrease in concentration too quickly. The work of Kravitz *et al.* highlights the difficulty of developing climate models that accurately represent the influence of volcanic-induced aerosols on climate, where the likely impact on surface temperature from the Kravitz *et al.* experiment would be a bias toward warm temperatures on the time scale of months.

Clearly there remain significant uncertainties and disagreements about the climatic effects of volcanic eruptions, showing a need for further research into this topic.

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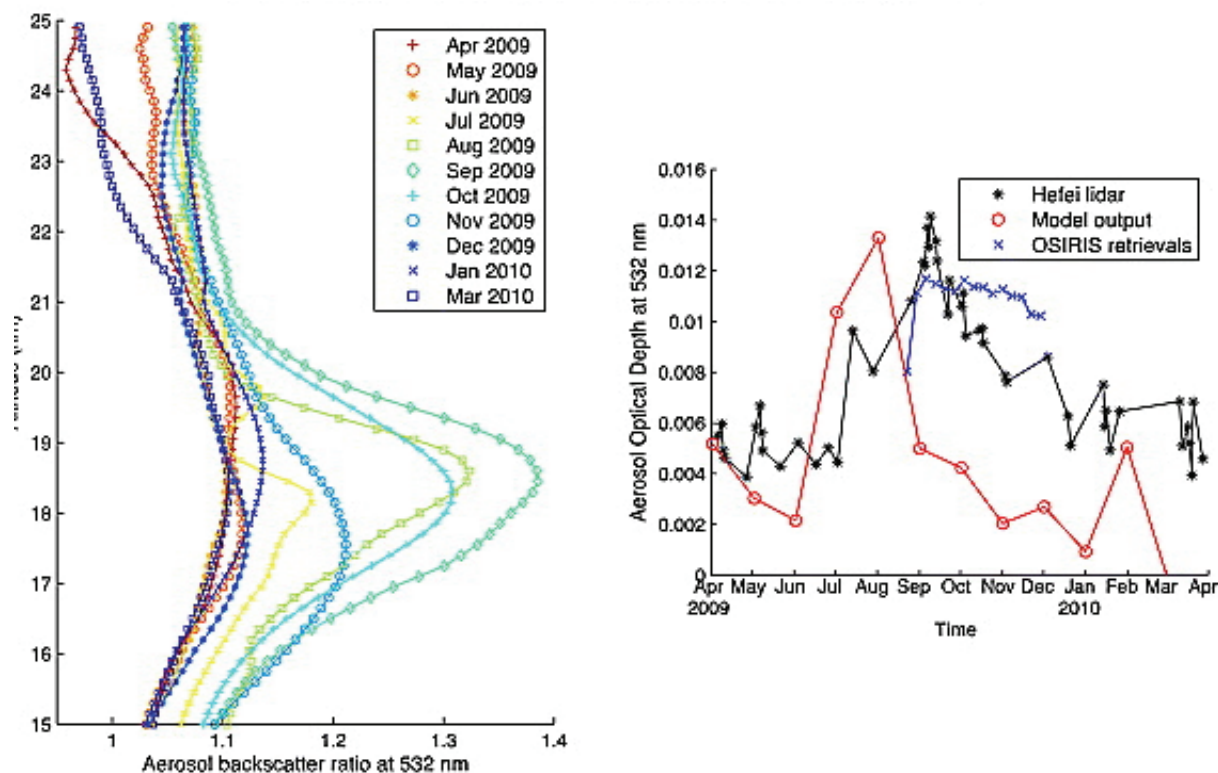


Figure 2.6.6.1. The LIDAR retrievals from Hefei, China as compared to model output and OSIRIS retrievals. (left) The monthly averages of backscatter as a function of altitude maximizing in September 2009. (right) The integrated (15–25 km) optical depth through the stratosphere for the LIDAR data (black), zonally averaged stratospheric aerosol optical depth calculated by the model in the grid latitude containing the Hefei LIDAR (28°–32°N) (red), and OSIRIS retrievals zonally averaged over the latitude band 30°–35°N (blue). Reprinted with permission from Kravitz, B., Robock, A., Bourassa, A., Deshler, T., Wu, D., Mattis, I., Finger, F., Hoffmann, A., Ritter, C., Bitar, L., Duck, T.J., and Barnes, J.E. 2011. Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. *Journal of Geophysical Research—Atmospheres* **116**: D18211, doi:10.1029/2010JD015501, Figure 11.

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3

Solar Forcing of Climate

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Key Findings

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Key Findings

The following points summarize the main findings of this chapter:

- Evidence is accruing that changes in Earth's surface temperature are largely driven by variations in solar activity. Examples of solar-controlled climate change epochs include the Medieval Warm Period, Little Ice Age and Early Twentieth Century (1910–1940) Warm Period.
- The Sun may have contributed as much as 66% of the observed twentieth century warming, and perhaps more.
- Strong empirical correlations have been reported from all around the world between solar variability and climate indices including temperature,

precipitation, droughts, floods, streamflow, and monsoons.

- IPCC models do not incorporate important solar factors such as fluctuations in magnetic intensity and overestimate the role of human-related CO₂ forcing.
- The IPCC fails to consider the importance of the demonstrated empirical relationship between solar activity, the ingress of galactic cosmic rays, and the formation of low clouds.
- The respective importance of the Sun and CO₂ in forcing Earth climate remains unresolved; current climate models fail to account for a plethora of known Sun-climate connections.
- The recently quiet Sun and extrapolation of solar

cycle patterns into the future suggest a planetary cooling may occur over the next few decades.

Introduction

The 2007 *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) claims “most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations [italics in the original]” (IPCC, 2007-I, p. 10). The authors go so far as to suggest there is a better-than-90-percent probability their assessment is true. Similar assertions are made in the IPCC’s forthcoming *Fifth Assessment Report* (AR5), which concludes “CO₂ is the strongest driver of climate change compared to other changes in the atmospheric composition, and changes in surface conditions. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers” (p. 7 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). But as demonstrated in Chapter 1 of this report, the global climate models upon which the IPCC rests its case are notoriously unreliable.

Chapter 2 documented feedback factors and forcings the IPCC has downplayed or overlooked, and Chapters 4–7 will show that real-world climate observations do not confirm the trends the IPCC claims should exist if its theory of CO₂-dominated climate change were true. This chapter explores an alternative theory of climate change the IPCC has rejected: that the *Sun’s* influence likely played the more dominant role in Earth’s climate over the past century and beyond.

The following statements taken from the Second Order Draft (SOD) of AR5 illustrate the IPCC’s rejection of the Sun’s influence as a major factor in contemporary climate change:

Changes in the astronomical alignment of the Sun and Earth induce cyclical changes in radiative forcing, but this is substantial only at millennial and longer timescales. (p. 8.30, SOD)

Quantification of the contributions of anthropogenic and natural forcing using multi-signal detection and attribution analyses show it is extremely likely that human activities (with very high confidence) have caused most (at least 50%) of the observed increase in global average temperatures since 1951. Detection and attribution

analyses show that the greenhouse gas warming contribution of 0.6°C–1.4°C was very likely greater than the observed warming of 0.6°C over the period 1951–2010. The response to aerosols and other anthropogenic forcings appears to be less clearly detectable using CMIP5 models than it was using CMIP3 models, but they probably contributed a net cooling over this period (Figure TS.8). Such analyses also indicate a trend of less than 0.1°C was attributable to combined forcing from solar irradiance variations and volcanic eruptions over this period. Taken together with other evidence this indicates that it is extremely unlikely that the contribution from solar forcing to the warming since 1950 was larger than that from greenhouse gases. Better understanding of pre-instrumental data shows that observed warming over this period is far outside the range of internal climate variability estimated from such records, and it is also far outside the range of variability simulated in climate models. Based on the surface temperature record, we therefore assess that it is virtually certain that warming since 1950 cannot be explained by internal variability alone. (p.23 of the Technical Summary, SOD)

Much of the IPCC’s examination of the possible influence of the Sun on Earth’s climate begins and ends with a discussion of total solar irradiance (TSI). According to the IPCC, secular trends in TSI are too small—estimated at only +0.04 [-0.01 to +0.09] W m⁻² since 1750—to have had much of an influence on the rising temperatures of the Current Warm Period. But as the material in this chapter shows, the IPCC is likely vastly underestimating this influence.

One possible reason, according to Soon *et al.* (2011), may rest in the fact that the low-amplitude TSI reconstruction estimates utilized by the IPCC and others (e.g., Lean *et al.*, 2005) are based on computer modeling by Wang *et al.* (2005), whose magnetic flux transport model “was not designed to model irradiance changes or to assess the solar energy budget.” In addition, Soon *et al.* note Wang *et al.*’s model “does not even contain a radiative transfer routine, which is essential to a proper description of solar physics” leaving Soon *et al.* to conclude “the Lean *et al.* (2005) reconstruction [used by the IPCC] is limited in its ability to describe variations in TSI.” Additional discussion of the reconstruction of the TSI history can be found in pp. 46–47 of Soon and Legates (2013).

A second reason the IPCC fails to acknowledge a significant solar influence on recent climate is that it

Solar Forcing of Climate

is looking for evidence (or rather a lack thereof) in the wrong places. Determining the correct or proper climatic metric to discern a solar-climate link may not be as straightforward as it would seem. From Lindzen (1994) to Karamperidou *et al.* (2012), for example, it has been proposed that perhaps the most relevant variable for studying how climate varies is the so-called Equator-to-Pole temperature gradient (EPTG) (traditionally, the Northern Hemisphere record is considered because the data coverage over the Southern Hemisphere is sparse and less reliable), not near-surface air temperatures, which Lindzen (1994) interpreted to be simply a residual product of the change in EPTG rather than the other way around.

Figure 3.1 illustrates the value of plotting TSI values with the Northern Hemisphere EPTG data. As indicated in the left panel of the figure, the close

global cloud cover, play a larger role in regulating Earth's temperature, precipitation, droughts, floods, monsoons, and other climate features than any past or expected human activities, including projected increases in greenhouse gas (GHG) emissions. We also discuss another mechanism involving the ultraviolet (UV) component of solar radiation, which fluctuates much more intensely than the visible light. The UV changes are known to cause significant changes in the stratosphere, affecting ozone, and recent studies suggest these effects may propagate down into the lower atmosphere through complex physical and chemical interactions.

We begin by analyzing research on solar irradiance, followed by an in-depth discussion of the cosmic ray theory of climate forcing. We then review empirical evidence linking solar variability to climate

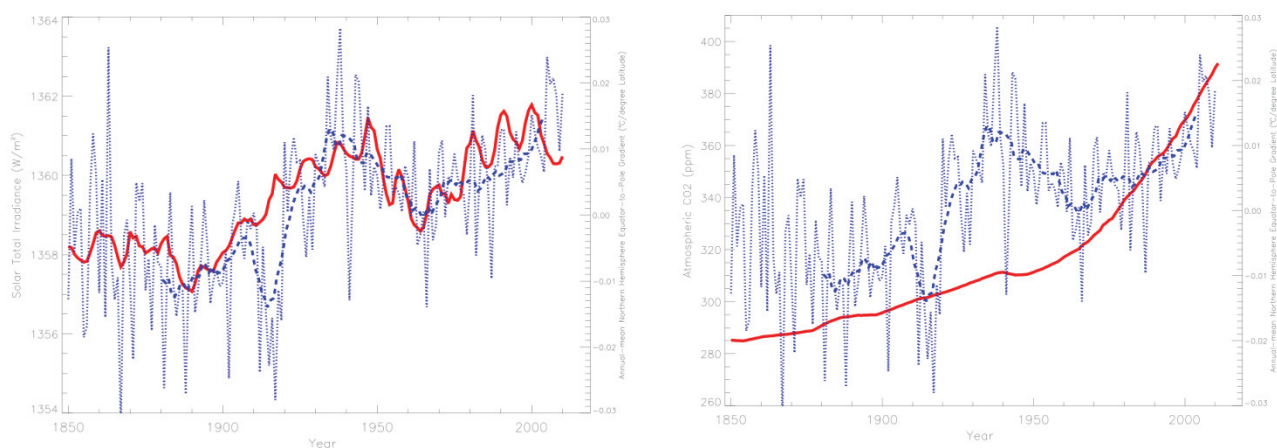


Figure 3.1. A comparison and contrast of the modulation of the Northern-Hemispheric equator-to-pole temperature gradient (both panels, dotted blue curves) by Total Solar Irradiance (TSI, left panel, solid red line) and by atmospheric CO₂ (right panel, solid red line). Adapted from Soon, W. and Legates, D.R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics* **93**: 45–56.

correlation between the data demonstrates the Sun's role in climate should not be discounted or outright dismissed, illustrating the potentially dominant role of the TSI in modulating climate on timescales of multiple decades to a century. A much weaker correlation is seen in the right panel of the figure, which displays atmospheric CO₂ data in the place of TSI, suggesting a much more tenuous and implausible relationship between atmospheric CO₂ and climate.

Throughout this chapter we examine evidence for an alternative theory of climate change: That variations in the Sun's radiation output and magnetic field, mediated by cosmic ray fluxes and changes in

phenomena in both ancient and modern times. Establishing this latter fact is important because regardless of the mechanism(s) involved, the fact that such tightly coupled relationships exist in nature supports the thesis that relatively small fluctuations in solar output can indeed produce significant changes in climate.

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3.1 Solar Irradiance

Changes in solar irradiance and ultraviolet radiation may yield a much larger influence on global climate than that envisioned by the IPCC to result from rising atmospheric CO₂ (see, for example, Soon *et al.* 2000). The often-used comparison of the *relative* radiative forcing of the Sun's irradiance versus rising atmospheric CO₂, as popularized in the IPCC reports, misses important physical insights.

In evaluating the overall significance of solar vs. CO₂ forcings, an apples-to-apples comparison would be to contrast the role of these two parameters on an *absolute* scale. For incoming solar radiation, the absolute forcing amounts to around 340 W m⁻² at the top of the atmosphere. The absolute forcing of atmospheric CO₂ is estimated at about 32–34 W m⁻² (see pp. 202–203 of Kiehl and Trenberth 1997). (A recent publication by Huang [2013, p. 1707], however, has calculated this value may be as high as 44.1 W m⁻².) Small changes in the absolute forcing of the Sun can easily result in values much larger than the predicted changes in radiative forcing typically associated with increasing CO₂, and these forcings could easily influence Earth's climate.

Evidence for a much stronger relationship between the Sun and Earth's climate than that envisioned by the IPCC is seen in many empirical studies. Karlén (1998), for example, examined proxy climate data related to changes in summer temperatures in Scandinavia over the past 10,000 years. This temperature record—derived from analyses of changes in the size of glaciers, changes in the altitude of the alpine tree-limit, and variations in the width of annual tree rings—was compared with contemporaneous solar irradiance data derived from ¹⁴C anomalies measured in tree rings. The record revealed both long- and short-term temperature fluctuations found to be “closely related” to the ¹⁴C-derived changes in solar irradiation, leading Karlén to conclude “the similarity between solar irradiation changes and climate indicate a solar influence on the Scandinavian and Greenland climates.” He further concluded “the frequency and magnitude of changes in climate during the Holocene [i.e., the current interglacial] do not support the opinion that the climatic change of the last 100 years is unique,” bluntly adding “there is no evidence of a human influence so far.”

Also writing just before the turn of the century, Lockwood *et al.* (1999) analyzed measurements of the near-Earth interplanetary magnetic field to determine the total magnetic flux leaving the Sun since 1868. Their analysis showed the total flux rose by a factor of 1.41 over the 32-year period 1964–1996, whereas surrogate measurements of the interplanetary magnetic field previous to this time indicated the total flux had increased by a factor of 2.3 since 1901. These findings and others linking changes in solar magnetic activity with terrestrial climate change led the authors to state “the variation [in the total solar magnetic flux] found here stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field.”

Parker (1999) noted the number of sunspots also roughly doubled since 1901, and one consequence of this phenomenon is a much more vigorous and slightly brighter Sun. Parker also drew attention to the fact that NASA spacecraft measurements had revealed the brightness (Br) of the Sun varies by the “change in $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle.” During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth-century Medieval Maximum), he pointed out,

brightness variations on the order of change in $\Delta Br/Br \approx 0.5\%$ typically occur (see Zhang *et al.* 1994, based on observational constraints from solar-type stars, for empirical support for the possibility of such a large-amplitude change). He noted the mean temperature (T) of the northern portion of Earth varied by 1 to 2°C in association with these variations in solar activity, stating, “we cannot help noting that $\Delta T/T \approx \Delta Br/Br$.”

Also in 1999, Chambers *et al.* (1999) noted research findings in both palaeoecology and solar science “indicate a greater role for solar forcing in Holocene climate change than has previously been recognized.” They found substantial evidence within the Holocene for solar-driven variations in Earth-atmosphere processes over a range of timescales stretching from the 11-year solar cycle to century-scale events. They acknowledge the absolute solar flux variations associated with these phenomena are rather small, but they identify a number of “multiplier effects” that can operate on solar rhythms in such a way that “minor variations in solar activity can be reflected in more significant variations within the Earth’s atmosphere.”

The three researchers also noted nonlinear responses to solar variability are inadequately represented in (in fact, essentially ignored by) the global climate models used by the IPCC to predict future CO₂-induced global warming, while at the same time other amplifier effects are used to model the hypothesized CO₂-induced global warming of the future, where CO₂ is only an initial perturber of the climate system which, according to the IPCC, sets other more powerful forces in motion that produce the bulk of the warming.

Bard *et al.* (2000) identified some of the many types of information that have been used to reconstruct past solar variability, including “the envelope of the SSN [sunspot number] 11-year cycle (Reid, 1991), the length and decay rate of the solar cycle (Hoyt and Schatten, 1993), the structure and decay rate of individual sunspots (Hoyt and Schatten, 1993), the mean level of SSN (Hoyt and Schatten, 1993; Zhang *et al.*, 1994; Reid, 1997), the solar rotation and the solar diameter (Nesme-Ribes *et al.*, 1993), and the geomagnetic aa index (Cliver *et al.*, 1998).” They also noted “Lean *et al.* (1995) proposed that the irradiance record could be divided into 2 superimposed components: an 11-year cycle based on the parameterization of sunspot darkening and facular brightening (Lean *et al.*, 1992), and a slowly varying background derived separately from studies of Sun-like stars (Baliunas and Jastrow, 1990),” and that

Solanki and Fligge (1998) had developed an even more convoluted technique.

Bard *et al.* used an entirely different approach. Rather than directly characterize some aspect of solar variability, they assessed certain consequences of that variability. Specifically, they noted magnetic fields of the solar wind deflect portions of the primary flux of charged cosmic particles in the vicinity of Earth, leading to reductions in the creation of cosmogenic nuclides in Earth’s atmosphere. Consequently, they reasoned histories of the atmospheric concentrations of ¹⁴C and ¹⁰Be can be used as proxies for solar activity, as noted many years earlier by Lal and Peters (1967).

In employing this approach to the problem, the four researchers first created a 1,200-year history of cosmonuclide production in Earth’s atmosphere from ¹⁰Be measurements of South Pole ice (Raisbeck *et al.*, 1990) and the atmospheric ¹⁴C/¹²C record as measured in tree rings (Bard *et al.*, 1997). This record was converted to total solar irradiance (TSI) values by “applying a linear scaling using the TSI values published previously for the Maunder Minimum,” when cosmonuclide production was 30 to 50 percent above the modern value. This process resulted in an extended TSI record suggesting, in their words, that “solar output was significantly reduced between AD 1450 and 1850, but slightly higher or similar to the present value during a period centered around AD 1200.” “It could thus be argued,” they say, “that irradiance variations may have contributed to the so-called ‘little ice age’ and ‘medieval warm period.’”

But Bard *et al.* downplay their own suggestion, because, as they report, “some researchers have concluded that the ‘little ice age’ and/or ‘medieval warm period’ [were] regional, rather than global events.” Noting the TSI variations they developed from their cosmonuclide data “would tend to force global effects,” they concluded they could not associate this global impetus for climate change with what other people were calling regional climatic anomalies. (Chapter 4 of this report demonstrates the Little Ice Age and Medieval Warm Period were in fact global in extent.)

Updated discussions of the complexity and physics involved in the reconstruction of the TSI are found in the work of Fontenla *et al.* (2011), Shapiro *et al.* (2011), and section 2 of Soon and Legates (2013). It is important to contrast these in-depth studies with other TSI reconstruction studies used by the IPCC, which are based on rather questionable statistical correlations: See, for example, equation 4 in

Steinhilber *et al.* (2009), where the inter-calibration, originally published in Figure 4c of Frohlich (2009), between TSI and the so-called open magnetic field strength was based on only three data points.

Rozelot (2001) conducted a series of analyses designed to determine whether phenomena related to variations in the radius of the Sun may have influenced Earth's climate over the past four centuries. He found "at least over the last four centuries, warm periods on the Earth correlate well with smaller apparent diameter of the Sun and colder ones with a bigger Sun." Although the results of this study were correlative and did not identify a physical mechanism capable of inducing significant climate change on Earth, Rozelot reports the changes in the Sun's radius are "of such magnitude that significant effects on the Earth's climate are possible."

Rigozo *et al.* (2001) created a history of sunspot numbers for the past 1,000 years "using a sum of sine waves derived from spectral analysis of the time series of sunspot number R_z for the period 1700–1999," and from this record they derived the strengths of parameters related to aspects of solar variability. The researchers state "the 1000-year reconstructed sunspot number reproduces well the great maximums and minimums in solar activity, identified in cosmonuclides variation records, and, specifically, the epochs of the Oort, Wolf, Sporer, Maunder, and Dalton Minimums, as well [as] the Medieval and Modern Maximums," the last of which they describe as "starting near 1900."

The mean sunspot number for the Wolf, Sporer, and Maunder Minimums was 1.36. For the Oort and Dalton Minimums it was 25.05; for the Medieval Maximum it was 53.00; and for the Modern Maximum it was 57.54. Compared with the average of the Wolf, Sporer, and Maunder Minimums, therefore, the mean sunspot number of the Oort and Dalton Minimums was 18.42 times greater; that of the Medieval Maximum was 38.97 times greater; and that of the Modern Maximum was 42.31 times greater. Similar strength ratios for the solar radio flux were 1.41, 1.89, and 1.97, respectively. For the solar wind velocity the corresponding ratios were 1.05, 1.10, and 1.11, and for the southward component of the interplanetary magnetic field they were 1.70, 2.54, and 2.67.

Both the Medieval and Modern Maximums in sunspot number and solar variability parameters stand out above all other periods of the past thousand years, with the Modern Maximum slightly besting the Medieval Maximum. These authors from Brazil and

Puerto Rico recently updated (see Echer *et al.* 2012) their analysis using NASA Goddard Institute for Space Studies temperature records and found a stronger statistical correlation of the surface temperature with the sunspot number data record in the 22-year Hale magnetic cycle band, with lags from zero to four years, than in the correlation in the 11-year solar cycle band.

Noting several spacecraft have monitored total solar irradiance (TSI) for the past 23 years, with at least two of them operating simultaneously at all times, and that TSI measurements made from balloons and rockets supplement the satellite data, Frohlich and Lean (2002) compared the composite TSI record with an empirical model of TSI variations based on known magnetic sources of irradiance variability, such as sunspot darkening and brightening, after which they described how "the TSI record may be extrapolated back to the seventeenth century Maunder Minimum of anomalously lower solar activity, which coincided with the coldest period of the Little Ice Age." This exercise "enables an assessment of the extent of post-industrial climate change that may be attributable to a varying Sun, and how much the Sun might influence future climate change."

Frohlich and Lean state "warming since 1650 due to the solar change is close to 0.4°C, with pre-industrial fluctuations of 0.2°C that are seen also to be present in the temperature reconstructions." It would appear solar variability can explain a significant portion of the warming of Earth in recovering from the global chill of the Little Ice Age. With respect to the future, the two solar scientists state, "solar forcing is unlikely to compensate for the expected forcing due to the increase of anthropogenic greenhouse gases which are projected to be about a factor of 3–6 larger." The magnitude of that anthropogenic forcing, however, has been computed by many different approaches to be much smaller than the value employed by Frohlich and Lean in making this comparison (Idso, 1998).

Douglass and Clader (2002) used multiple regression analysis to separate surface and atmospheric temperature responses to solar irradiance variations over the past two-and-a-half solar cycles (1979–2001) from temperature responses produced by variations in ENSO and volcanic activity. Based on the satellite-derived lower tropospheric temperature record, they evaluated the sensitivity (k) of temperature (T) to solar irradiance (I), where temperature sensitivity to solar irradiance is defined

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as $k = \Delta T / \Delta I$, obtaining the result of $k = 0.11 \pm 0.02^\circ\text{C}/(\text{W}/\text{m}^2)$. Similar analyses based on the radiosonde temperature record of Parker *et al.* (1997) and the surface air temperature records of Jones *et al.* (2001) and Hansen and Lebedeff (1987, with updates) produced k values of 0.13, 0.09, and $0.11^\circ\text{C}/(\text{W}/\text{m}^2)$, respectively, with the identical standard error of $\pm 0.02^\circ\text{C}/(\text{W}/\text{m}^2)$. In addition, they reported White *et al.* (1997) derived a decadal timescale solar sensitivity of $0.10 \pm 0.02^\circ\text{C}/(\text{W}/\text{m}^2)$ from a study of upper ocean temperatures over the period 1955–1994 and Lean and Rind (1998) derived a value of $0.12 \pm 0.02^\circ\text{C}/(\text{W}/\text{m}^2)$ from a reconstructed paleotemperature record spanning the period 1610–1800.

Douglass and Clader concluded, “the close agreement of these various independent values with our value of $0.11 \pm 0.02 [^\circ\text{C}/(\text{W}/\text{m}^2)]$ suggests that the sensitivity k is the same for both decadal and centennial time scales and for both ocean and lower tropospheric temperatures.” They further suggest if these values of k hold true for centennial time scales, which appears to be the case, their high-end value implies a surface warming of 0.2°C over the past 100 years in response to the $1.5 \text{ W}/\text{m}^2$ increase in solar irradiance inferred by Lean (2000) for this period. This warming represents approximately one-third of the total increase in global surface air temperature estimated by Parker *et al.* (1997), 0.55°C , and Hansen *et al.* (1999), 0.65°C , for the same period. It does not, however, include potential indirect effects of more esoteric solar climate-affecting phenomena, such as those from cosmic rays as discussed in Section 3.2 of this chapter, that also could have been operative over this period.

Foukal (2002) analyzed the findings of spaceborne radiometry and reported “variations in total solar irradiance, S , measured over the past 22 years, are found to be closely proportional to the difference in projected areas of dark sunspots, AS , and of bright magnetic plage elements, APN , in active regions and in enhanced network.” They also found “this difference varies from cycle to cycle and is not simply related to cycle amplitude itself,” which suggests there is “little reason to expect that S will track any of the familiar indices of solar activity.” On the other hand, he notes, “empirical modeling of spectro-radiometric observations indicates that the variability of solar ultraviolet flux, FUV , at wavelengths shorter than approximately 250 nm, is determined mainly by APN alone.”

Using daily data from the Mt. Wilson Observatory covering the period 1905–1984 and

partially overlapping data from the Sacramento Peak Observatory that extended through 1999, Foukal derived time series of total solar and UV irradiances between 1915 and 1999, which he then compared with global temperature data for that period. He reported, “correlation of our time series of UV irradiance with global temperature, T , accounts for only 20% of the global temperature variance during the 20th century” but “correlation of our total irradiance time series with T accounts statistically for 80% of the variance in global temperature over that period.”

The UV findings of Foukal were not impressive, but the results of his total solar irradiance analysis were, leading him to state “the possibility of significant driving of twentieth century climate by total irradiance variation cannot be dismissed.” Although the magnitude of the total solar effect was determined to be “a factor 3–5 lower than expected to produce a significant global warming contribution based on present-day climate model sensitivities,” what Foukal calls the “high correlation between S and T ” strongly suggests changes in S largely determine changes in T , confirmation of which likely awaits only what he refers to as an “improved understanding of possible climate sensitivity to relatively small total irradiance variation.”

Willson and Mordvinov (2003) analyzed total solar irradiance (TSI) data obtained from different satellite platforms over the period 1978–2002, attempting to resolve various small but important inconsistencies among them. In doing so, they recognized “construction of TSI composite databases will not be without its controversies for the foreseeable future.” Nevertheless, their most interesting result, in the estimation of the two researchers, was their confirmation of a $+0.05\%$ /decade trend between the minima separating solar cycles 21–22 and 22–23, which they say “appears to be significant.”

Willson and Mordvinov say the finding of the 0.05 percent/decade minimum-to-minimum trend “means that TSI variability can be caused by unknown mechanisms other than the solar magnetic activity cycle,” which means “much longer time scales for TSI variations are therefore a possibility,” which they say “has obvious implications for solar forcing of climate.” Undiscovered long-term variations in total solar irradiance could explain centennial-scale climate variability, which Bond *et al.* (2001) already have demonstrated to be related to solar activity, as well as the millennial-scale climatic

oscillation that pervades both glacial and interglacial periods (Oppo *et al.*, 1998; Raymo *et al.*, 1998).

Like Willson and Mordvinov, Foukal (2003) acknowledged “recent evidence from ocean and ice cores suggests that a significant fraction of the variability in northern hemisphere climate since the last Ice Age correlates with solar activity (Bond *et al.*, 2001),” while noting “a recent reconstruction of S [total solar irradiance] from archival images of spots and faculae obtained daily from the Mt. Wilson Observatory in California since 1915 shows remarkable agreement with smoothed global temperature in the 20th century,” citing his own work of 2002. He acknowledged the observed variations in S between 1978 and 2002 were not large enough to explain the observed temperature changes on Earth within the context of normal radiative forcing and proceeded to consider the status of research into subjects that might explain this situation. He reviewed then-current knowledge relative to the idea that “the solar impact on climate might be driven by other variable solar outputs of ultraviolet radiation or plasmas and fields via more complex mechanisms than direct forcing of tropospheric temperature” and concluded, “we cannot rule out multi-decadal variations in S sufficiently large to influence climate, yet overlooked so far through limited sensitivity and time span of our present observational techniques.”

Citing the work of Herman and Goldberg (1978), Pittcock (1983), Hoyt and Schatten (1997), and van Loon and Labitzke (2000), Thejll *et al.* (2003) note “apparent relations between solar activity, or parameters closely related to solar activity, and climate data have often been reported.” Noting further that a substantial portion of Northern Hemispheric climate variability is associated with the North Atlantic Oscillation (NAO), as described by Hurrell *et al.* (2001), they report the activity of the NAO has been found to be related to solar-geomagnetic parameters (Bucha and Bucha, 1998; Boberg and Lundstedt, 2002; Kodera, 2002).

Thejll *et al.* examined spatial and temporal relationships among the geomagnetic index (*Ap*), the NAO, stratospheric geopotential height, and sea level pressure, revealing “significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000,” but “for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere.” By using “Monte Carlo simulations of the statistical procedures applied to suitable surrogate

data,” they also concluded these correlations are due to the existence of a “real physical link.” They also noted in the 1973–2000 period only the winter season series are significantly correlated, which they say “is consistent with the notion that the solar-climate link works through the stratosphere.”

Thejll *et al.* stated their findings may be explained in two different ways: either the influence of the Sun increased through time, reaching a strong enough level in the 1970s to make the correlations they studied become statistically significant, or the state of the atmosphere changed in the 1970s, becoming more sensitive to the solar influence than it had been. Their findings strengthen the case for solar-induced perturbations being propagated downward from the stratosphere to the troposphere (Hartley *et al.*, 1998; Carslaw *et al.*, 2002).

Ineson *et al.* (2011) modeled the effects of realistic solar UV (200–320 nm) irradiance changes between solar activity minima and maxima in the stratosphere and mesosphere, finding weaker westerly winds during the winters with a less active Sun that may drive cold winters in Northern Europe and the United States and mild winters over Southern Europe and Canada, as observed in recent years. The observational analyses by Hood *et al.* (2013) add insight into the specific regional patterns of the near-surface responses that likely originated from the solar UV forcing of ozone and related wind-thermal fields in the stratosphere. These authors note “the observational analyses ... provide additional evidence that a surface climate response to 11-yr solar forcing during the boreal winter season is detectable in global SLP and SST records extending back to the 19th century. The response is most clearly detected in the Pacific sector where a positive solar SLP response anomaly is obtained over the Aleutian region and a corresponding positive SST response anomaly extends across the midlatitude North Pacific ... The SLP response in the Arctic is generally negative supporting the hypothesis that the solar response is similar to a positive Arctic Oscillation mode. However, only a weak and marginally significant SST response is obtained in the equatorial eastern Pacific so the response differs from that which characterizes a La Niña event ... Analyses of the observed response as a function of phase lag indicate that the solar SLP response evolves from a predominately negative AO structure a few years prior to solar maximum to a predominately positive AO structure at and following solar maximum. ... The amplitudes of the Aleutian SLP response anomaly and the corresponding positive

SST anomaly maximize at zero lag.”

As Hood *et al.* (2013) declared, “in general, models should be validated by observations rather than the other way around.”

To be sure, some of the Sun-climate relation studies have been challenged. In 2004, Damon and Laut (2004) reported what they described as errors made by Friis-Christensen and Lassen (1991), Svensmark and Friis-Christensen (1997), Svensmark (1998), and Lassen and Friis-Christensen (2000) in their presentation of solar activity data correlated with terrestrial temperature data. The Danish scientists’ error, in the words of Damon and Laut, was “adding to a heavily smoothed (‘filtered’) curve, four additional points covering the period of global warming, which were only partially filtered or not filtered at all.” This in turn led to an apparent dramatic increase in solar activity over the last quarter of the twentieth century that closely matched the equally dramatic rise in temperature manifest by the Northern Hemispheric temperature reconstruction of Mann *et al.* (1998, 1999) over the same period. With the acquisition of additional solar activity data in subsequent years, however, and with what Damon and Laut called the proper handling of the numbers, the late twentieth century dramatic increase in solar activity disappears.

This new result, to quote Damon and Laut, means “the sensational agreement with the recent global warming, which drew worldwide attention, has totally disappeared.” In reality, however, it is only the agreement with the last quarter-century of the discredited Mann *et al.* “hockey stick” temperature history that has disappeared. This new disagreement is important, for the Mann *et al.* temperature reconstruction is likely in error over this period of time. (See Chapter 4.)

Using a nonlinear non-stationary time series technique called empirical mode decomposition, Coughlin and Tung (2004) analyzed monthly mean geopotential heights and temperatures obtained from Kalnay *et al.* (1996) from 1000 hPa to 10 hPa over the period January 1958 to December 2003. This work revealed the existence of five oscillations and a trend in both data sets. The fourth of these oscillations has an average period of 11 years and indicates enhanced warming during times of maximum solar radiation. As the two researchers describe it, “the solar flux is positively correlated with the fourth modes in temperature and geopotential height almost everywhere [and] the overwhelming picture is that of a positive correlation between the solar flux and this

mode throughout the troposphere.”

Coughlin and Tung concluded “the atmosphere warms during the solar maximum almost everywhere over the globe.” And the unfailing omnipresent impact of this small forcing (a 0.1 percent change in the total energy output of the Sun from cycle minimum to maximum) suggests any longer-period oscillations of the solar inferno could be causing the even greater centennial- and millennial-scale oscillations of temperature observed in paleo-temperature data from around the world.

Widespread measurements have been made since the late 1950s of the flux of solar radiation received at the surface of Earth, and nearly all of these measurements reveal a sizeable decline in the surface receipt of solar radiation that was not reversed until the mid-1980s, as noted by Wild *et al.* (2005). During this time, there was also a noticeable dip in Earth’s surface air temperature, after which temperatures rose at a rate and to a level of warmth the IPCC claims were without precedent over the past one to two millennia, and which they attribute to similarly unprecedented increases in greenhouse gas concentrations, mostly notably CO₂.

This reversal of the decline in the amount of solar radiation incident upon Earth’s surface, in the words of Wild *et al.*, “is reconcilable with changes in cloudiness and atmospheric transmission and may substantially affect surface climate.” “Whereas the decline in solar energy could have counterbalanced the increase in down-welling longwave energy from the enhanced greenhouse effect before the 1980s,” they note, “the masking of the greenhouse effect and related impacts may no longer have been effective thereafter, enabling the greenhouse signals to become more evident during the 1990s.” Qualitatively, this scenario sounds plausible, but when the magnitude of the increase in the surface-received flux of solar radiation over the 1990s is considered, the statement is seen to be rather disingenuous.

Over the range of years for which high-quality data were available to them (1992–2002), Wild *et al.* determined the mean worldwide increase in clear-sky insolation averaged 0.68 Wm⁻² per year, which increase they found to be “comparable to the increase under all-sky conditions.” Consequently, for that 10-year period, these data suggest the total increase in solar radiation received at the surface of Earth should have been something on the order of 6.8 Wm⁻², not significantly different from what is implied by the satellite and “Earthshine” data of Palle *et al.* (2004), although the satellite data of Pinker *et al.* (2005)

suggest an increase only about a third as large for this period.

Putting these numbers in perspective, Charlson *et al.* (2005) report the longwave radiative forcing provided by all greenhouse gas increases since the beginning of the industrial era has amounted to only 2.4 Wm^{-2} , citing the work of Anderson *et al.* (2003), while Palle *et al.* say “the latest IPCC report argues for a 2.4 Wm^{-2} increase in CO_2 longwave forcing since 1850.” The longwave forcing of greenhouse gases over the 1990s thus would have been but a fraction of a fraction of the observed increase in the contemporary receipt of solar radiation at the surface of Earth. To suggest, as Wild *et al.* do, that the increase in insolation experienced at the surface of Earth over the 1990s may have enabled anthropogenic greenhouse gas signals of that period to become more evident seems incongruous, as their suggestion implies the bulk of the warming of that period was due to increases in greenhouse gas concentrations, when the solar component of the temperature forcing was clearly much greater. This incongruity is exacerbated by the fact that methane concentrations rose ever more slowly over this period, apparently stabilizing near the period’s end (see Chapter 2). Consequently, a much more logical conclusion would be that the primary driver of the global warming of the 1990s was the large increase in global surface-level insolation.

Soon (2005) explored the question of which variable was the dominant driver of twentieth-century temperature change in the Arctic—rising atmospheric CO_2 concentrations or variations in solar irradiance—by examining what roles the two variables may have played in decadal, multidecadal, and longer-term variations in surface air temperature (SAT). He performed a number of statistical analyses on a composite Arctic-wide SAT record constructed by Polyakov *et al.* (2003), global CO_2 concentrations taken from estimates given by the NASA GISS climate modeling group, and a total solar irradiance (TSI) record developed by Hoyt and Schatten (1993, updated by Hoyt in 2005) for the period 1875–2000.

These analyses indicated a much stronger statistical relationship between SATs and TSI than between SATs and CO_2 . Solar forcing generally explained more than 75 percent of the variance in decadal-smoothed seasonal and annual Arctic SATs, whereas CO_2 forcing explained only between 8 and 22 percent of the variance. Wavelet analysis further supported the case for solar forcing of the SAT record, revealing similar time-frequency

characteristics for annual and seasonally averaged temperatures at decadal and multidecadal time scales. By contrast, wavelet analysis gave little or no indication of a CO_2 forcing of Arctic SSTs.

Lastovicka (2006) summarized recent advancements in the field, saying “new results from various space and ground-based experiments monitoring the radiative and particle emissions of the Sun, together with their terrestrial impact, have opened an exciting new era in both solar and atmospheric physics,” stating “these studies clearly show that the variable solar radiative and particle output affects the Earth’s atmosphere and climate in many fundamental ways.”

Bard and Frank (2006) examined “changes on different time scales, from the last million years up to recent decades,” and in doing so assessed recent claims that “the variability of the Sun has had a significant impact on global climate.” The two researchers conclude the role of solar activity in causing climate change “remains unproven.” But they state in the concluding sentence of their abstract, “the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: the so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500–1800).”

Beer *et al.* (2006) explored solar variability and its possible effects on Earth’s climate, focusing on two types of variability in the flux of solar radiation incident on Earth. The first type, in their words, “is due to changes in the orbital parameters of the Earth’s position relative to the Sun induced by the other planets,” which arises from gravitational perturbations that “induce changes with characteristic time scales in the eccentricity ($\sim 100,000$ years), the obliquity (angle between the equator and the orbital plane, $\sim 40,000$ years) and the precession of the Earth’s axis ($\sim 20,000$ years).” The second type of variability is due to variability within the Sun itself.

With respect to the latter variability, the three researchers point out direct observations of total solar irradiance above Earth’s atmosphere have been made over only the past quarter-century, whereas observations of sunspots have been made and recorded for approximately four centuries. In between the time scales of these two types of measurements fall neutron count rates and aurora counts. Therefore, ^{10}Be and other cosmogenic radionuclides (such as ^{14}C)—stored in ice, sediment cores, and tree rings—

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currently provide our only means of inferring solar irradiance variability on a millennial time scale. These cosmogenic nuclides “clearly reveal that the Sun varies significantly on millennial time scales and most likely plays an important role in climate change.” In reference to their ^{10}Be -based derivation of a 9,000-year record of solar modulation, Beer *et al.* note its “comparison with paleoclimatic data provides strong evidence for a causal relationship between solar variability and climate change.”

Nicola Scafetta, a research scientist in the Duke University physics department, and Bruce West, chief scientist in the mathematical and information science directorate of the U.S. Army Research Office in Research Triangle Park, North Carolina, developed (Scafetta and West, 2006a) “two distinct TSI reconstructions made by merging in 1980 the annual mean TSI proxy reconstruction of Lean *et al.* (1995) for the period 1900–1980 and two alternative TSI satellite composites, ACRIM (Willson and Mordvinov, 2003), and PMOD (Frohlich and Lean, 1998), for the period 1980–2000,” after which they used a climate sensitivity transfer function to create twentieth century temperature histories. Their results suggested the Sun contributed some 46 to 49 percent of the 1900–2000 warming of Earth. Considering there may have been uncertainties of 20 to 30 percent in their sensitivity parameters, the two researchers suggest the Sun may have been responsible for as much as 60 percent of the twentieth century temperature rise.

Scafetta and West say the role of the Sun in twentieth century global warming has been significantly underestimated by the climate modeling community, with various energy balance models producing estimates of solar-induced warming over this period that are “two to ten times lower” than what they found. The two researchers say “the models might be inadequate because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular.” They also note “theoretical models usually acknowledge as solar forcing only the direct TSI forcing,” thereby ignoring “possible additional climate effects linked to solar magnetic field, UV radiation, solar flares and cosmic ray intensity modulations.” It also should be noted some of these phenomena may to some degree be independent of, and thereby add to, the simple TSI forcing Scafetta and West employed, suggesting the totality of solar activity effects on climate may be even greater than what they calculated.

In a second study published that year, Scafetta and West (2006b) pointed out nearly all attribution studies begin with predetermined forcing and feedback mechanisms in the models they employ. “One difficulty with this approach,” according to Scafetta and West, “is that the feedback mechanisms and alternative solar effects on climate, since they are only partially known, might be poorly or not modeled at all.” Consequently, “to circumvent the lack of knowledge in climate physics,” they adopt “an alternative approach that attempts to evaluate the total direct plus indirect effect of solar changes on climate by comparing patterns in the secular temperature and TSI reconstructions,” where “a TSI reconstruction is not used as a radiative forcing, but as a proxy [for] the entire solar dynamics.” They proceed on the assumption that “the secular climate sensitivity to solar change can be phenomenologically estimated by comparing ... solar and temperature records during the pre-industrial era, when, reasonably, only a negligible amount of anthropogenic-added climate forcing was present” and “the Sun was the only realistic force affecting climate on a secular scale.”

Scafetta and West used the Northern Hemispheric temperature reconstruction of Moberg *et al.* (2005), three alternative TSI proxy reconstructions developed by Lean *et al.* (1995), Lean (2000), and Wang *et al.* (2005), and a scale-by-scale transfer model of climate sensitivity to solar activity changes they developed (Scafetta and West, 2005, 2006a). They found a “good correspondence between global temperature and solar induced temperature curves during the pre-industrial period, such as the cooling periods occurring during the Maunder Minimum (1645–1715) and the Dalton Minimum (1795–1825).” In addition, they note since the time of the seventeenth century solar minimum, “the Sun has induced a warming of $\Delta T \sim 0.7 \text{ K}$ ” and “this warming is of the same magnitude [as] the cooling of $\Delta T \sim 0.7 \text{ K}$ from the medieval maximum to the 17th century minimum.” This finding, they write, “suggests the presence of a millenarian solar cycle, with ... medieval and contemporary maxima, driving the climate of the last millennium,” as was first suggested fully three decades ago by Eddy (1976) in his seminal study of the Maunder Minimum.

Scafetta and West say their work provides substantive evidence for the likelihood that “solar change effects are greater than what can be explained by several climate models,” citing Stevens and North (1996), the Intergovernmental Panel on Climate Change (2001), Hansen *et al.* (2002), and Foukal *et*

al. (2004), and they note a solar change “might trigger several climate feedbacks and alter the greenhouse gas (H₂O, CO₂, CH₄, etc.) concentrations, as 420,000 years of Antarctic ice core data would also suggest (Petit *et al.*, 1999),” once again reiterating “most of the Sun-climate coupling mechanisms are probably still unknown” and “might strongly amplify the effects of small solar activity increase.” The researchers note in the twentieth century there was “a clear surplus warming” above and beyond what is suggested by their solar-based temperature reconstruction, such that something in addition to the Sun may have been responsible for approximately 50 percent of the total global warming since 1900.

This anomalous increase in temperature, it could be argued, was due to anthropogenic greenhouse gas emissions. However, Scafetta and West say the temperature difference since 1975, where the most noticeable part of the discrepancy occurred, may have been due to “spurious non-climatic contamination of the surface observations such as heat-island and land-use effects (Pielke *et al.*, 2002; Kalnay and Cai, 2003),” which they say is also suggested by “an anomalous warming behavior of the global average land temperature vs. the marine temperature since 1975 (Brohan *et al.*, 2006).”

In their next paper, Scafetta and West (2007) reconstructed a phenomenological solar signature (PSS) of climate for the Northern Hemisphere for the past four centuries that matches relatively well the instrumental temperature record since 1850 and the paleoclimate temperature proxy reconstruction of Moberg (2005). The period from 1950 to 2010 showed excellent agreement between 11- and 22-year PSS cycles when compared to smoothed average global temperature data and the global cooling that occurred since 2002.

Continuing their effort to identify a solar signal in Earth’s global temperature record, in the March 2008 issue of *Physics Today* Scafetta and West (2008) began by noting the IPCC concludes “the contribution of solar variability to global warming is negligible, to a certainty of 95%,” which would appear to stack the deck heavily against their being successful. Whereas “the statistical variability in Earth’s average temperature is interpreted as noise” by most climate modelers and “thought to contain no useful information,” Scafetta and West proposed “the variations in Earth’s temperature are not noise, but contain substantial information about the source of variability,” which they suggest is total solar irradiance, or TSI. The two researchers further

suggest “variations in TSI are indicative of the Sun’s turbulent dynamics,” as represented by “changes in the number, duration, and intensity of solar flares and sunspots, and by the intermittency in the time intervals between dark spots and bright faculae,” which variability has the capacity to “move the global temperature up and down for tens or even hundreds of years.”

In providing support for their hypothesis, Scafetta and West point out “both the fluctuations in TSI, using the solar flare time series as a surrogate, and Earth’s average temperature time series are observed to have inverse power-law statistical distributions,” and the inverse power-law index “turns out to be the same for both the solar flare and temperature anomaly time series,” citing the work of Scafetta and West (2003). This suggests “the statistics of the temperature anomalies inherit the statistical structure that was evident in the intermittency of the solar flare data.” This finding led the two researchers to conclude “the Sun is influencing climate significantly more than the IPCC report claims” and “the current anthropogenic contribution to global warming is significantly overestimated.” Citing Scafetta and West (2007), they “estimate that the Sun could account for as much as 69% of the increase in Earth’s average temperature, depending on the TSI reconstruction used.”

In 2009, Scafetta and Richard C. Willson, senior research scientist at Columbia’s Center for Climate Systems Research, addressed whether TSI increased from 1980 to 2002 (Scafetta and Willson, 2009). The IPCC assumed there was no increase by adopting the TSI satellite composite produced by the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (see Frohlich, 2006). PMOD assumed the NIMBUS7 TSI satellite record artificially increased its sensitivity during the ACRIM-gap (1999.5–1991.75) and therefore reduced the NIMBUS7 record by 0.86 W/m² during the ACRIM-gap period; consequently, the TSI results changed little since 1980. This PMOD adjustment of NIMBUS7 TSI satellite data was never acknowledged by the experimental teams (Willson and Mordvinov, 2003; supporting material in Scafetta and Willson, 2009).

Scafetta and Willson proposed to resolve the ACRIM-gap calibration controversy by developing a TSI model using a proxy model based on variations of the surface distribution of solar magnetic flux designed by Krivova *et al.* (2007) to bridge the two-year gap between ACRIM1 and ACRIM2. They use this to bridge “mixed” versions of ACRIM and

PMOD TSI before and after the ACRIM-gap. Both “mixed” models show, in the authors’ words, “a significant TSI increase of 0.033%/decade between the solar activity minima of 1986 and 1996, comparable to the 0.037% found in the TSI satellite ACRIM composite.” They conclude “increasing TSI between 1980 and 2000 could have contributed significantly to global warming during the last three decades. Current climate models have assumed that TSI did not vary significantly during the last 30 years and have, therefore, underestimated the solar contribution and overestimated the anthropogenic contribution to global warming.”

Krivova *et al.* (2007) noted “strong interest” in the subject of long-term variations of total solar irradiance or TSI “due to its potential influence on global climate,” suggesting “only a reconstruction of solar irradiance for the pre-satellite period with the help of models can aid in gaining further insight into the nature of this influence.” They developed a history of TSI “from the end of the Maunder minimum [about AD 1700] to the present based on variations of the surface distribution of the solar magnetic field,” which was “calculated from the historical record of the sunspot number using a simple but consistent physical model,” e.g., that of Solanki *et al.* (2000, 2002).

Krivova *et al.* report their model “successfully reproduces three independent data sets: total solar irradiance measurements available since 1978, total photospheric magnetic flux since 1974, and the open magnetic flux since 1868,” which was “empirically reconstructed using the geomagnetic *aa*-index.” Based on this model, they calculated an increase in TSI since the Maunder minimum somewhere in the range of 0.9-1.5 Wm⁻², which encompasses the results of several independent reconstructions derived over the past few years. In the final sentence of their paper, however, they note “all the values we obtain are significantly below the Δ TSI values deduced from stellar data and used in older TSI reconstructions,” the results of which range from 2 to 16 Wm⁻².

Although there remains a degree of uncertainty about the true magnitude of the TSI change experienced since the end of the Maunder Minimum, the wide range of possible values suggests long-term TSI variability cannot be rejected as a plausible cause of the majority of the global warming seen since the Little Ice Age. The results of many of the studies reviewed in this section argue strongly for this scenario, while others suggest it is the only explanation that fits all the data.

Goode and Pallé (2007) state at the outset of their paper, “we know that there are terrestrial imprints of the solar cycle” even when “the implied changes in solar irradiance seem too weak to induce an imprint.” They try to discern how such a small solar signal might induce such a large climatic response. They reviewed data shedding light on two important parameters of climate change—solar irradiance and terrestrial reflectance—which together determine the net sunlight absorbed by the Earth-ocean-atmosphere system, thereby setting the stage for the system’s ultimate thermal response to the forcing they provide.

In attempting to “illustrate the possibilities of a Sun-albedo link,” Goode and Pallé conclude “reflectance changes like the ones observed during the past two decades, if maintained over longer time periods, are sufficient to explain climate episodes like the ‘Little Ice Age’ without the need for significant solar irradiance variations.” While they say their analysis of the problem “cannot be used to argue for a solar cycle dependence,” they also note “it is ... difficult to dismiss the possibility of a solar-albedo link.”

Goode and Pallé conclude, “regardless of its possible solar ties,” Earth’s large-scale reflectance “is a much more variable climate parameter than previously thought and, thus, deserves to be studied in as much detail as changes in the Sun’s output or changes in the Earth’s atmospheric infrared emission produced by anthropogenic greenhouse gases.” They note “long-term records of the Earth’s reflectance will provide crucial input for general circulation climate models, and will significantly increase our ability to assess and predict climate change.”

Shaviv (2008) attempted to quantify solar radiative forcing using oceans as a calorimeter. He evaluated three independent measures of net ocean heat flux over five decades, sea level change rate from twentieth century tide gauge records, and sea surface temperature. He found a “very clear correlation between solar activity and sea level” including the 11-year solar periodicity and phase, with a correlation coefficient of $r=0.55$. He also found “the total radiative forcing associated with solar cycles variations is about 5 to 7 times larger than those associated with the TSI variations, thus implying the necessary existence of an amplification mechanism, though without pointing to which one.”

Shaviv argues “the sheer size of the heat flux, and the lack of any phase lag between the flux and the driving force further implies that it cannot be part of an atmospheric feedback and very unlikely to be part

of a coupled atmosphere-ocean oscillation mode. It must therefore be the manifestation of real variations in the global radiative forcing.” This provides “very strong support for the notion that an amplification mechanism exists. Given that the CRF [Cosmic Ray Flux]/climate links predicts the correct radiation imbalance observed in the cloud cover variations, it is a favorable candidate.” These results, Shaviv says, “imply that the climate sensitivity required to explain historic temperature variations is smaller than often concluded.”

Pallé *et al.* (2009) reanalyzed the overall reflectance of sunlight from Earth (“Earthshine”) and recalibrated the CERES satellite data to obtain consistent results for Earth’s solar reflectance. According to the authors, “Earthshine and FD [flux data] analyses show contemporaneous and climatologically significant increases in the Earth’s reflectance from the outset of our Earthshine measurements beginning in late 1998 roughly until mid-2000. After that and to date, all three show a roughly constant terrestrial albedo, except for the FD data in the most recent years. Using satellite cloud data and Earth reflectance models, we also show that the decadal-scale changes in Earth’s reflectance measured by Earthshine are reliable and are caused by changes in the properties of clouds rather than any spurious signal, such as changes in the Sun-Earth-Moon geometry.”

Ohmura (2009) reviewed surface solar irradiance at 400 sites across the globe, finding a brightening phase from the 1920s to 1960s, followed by a 20-year dimming phase from 1960 to 1980. Then there was another 15-year brightening phase from 1990 to 2005. Ohmura finds “aerosol direct and indirect effects played about an equal weight in changing global solar radiation. The temperature sensitivity due to radiation change is estimated at 0.05 to 0.06 K/(W m⁻²).”

Long *et al.* (2009) analyzed “all-sky and clear-sky surface downwelling shortwave radiation and bulk cloud properties” from 1995 through 2007. They “show that widespread brightening has occurred over the continental United States ... averaging about 8 W m⁻²/decade for all-sky shortwave and 5 W m⁻²/decade for the clear-sky shortwave. This all-sky increase is substantially greater than the (global) 2 W m⁻²/decade previously reported...” Their “results show changes in dry aerosols and/or direct aerosol effects alone cannot explain the observed changes in surface shortwave (SW) radiation, but it is likely that changes in cloudiness play a significant role.”

These observations by Shaviv, Pallé, Ohmura,

and Long *et al.* each point to major variations in Earth’s radiative budget caused by changes in aerosols and clouds. Both are affected by natural and anthropogenic causes, including aircraft, power plants, cars, cooking, forest fires, and volcanoes. Natural forces—solar activity and cosmic rays—also modulate clouds. Later in this chapter, in Section 3.3.5, empirical evidence uncovered by Soon *et al.* (2011) for the simultaneous multidecadal modulation of the TSI and near-surface solar radiation from a unique sunshine duration record by the Japanese Meteorological Agency is discussed. When GCMs ignore or underestimate causes or modulation by solar cycles, magnetic fields, and/or cosmic rays, they overestimate the climate sensitivity of anthropogenic impacts.

Scafetta (2012) developed an “astronomical-based empirical harmonic climate model” that assumed Earth’s climate system is resonating with, or synchronized to, a set of natural frequencies of the solar system (Scafetta, 2010, 2011). He indicates the major hypothesized mechanism upon which the model is based is that “the planets, in particular Jupiter and Saturn, induce solar or heliospheric oscillations that induce equivalent oscillations in the electromagnetic properties of the [Earth’s] upper atmosphere,” which in turn induces similar cycles in cloud cover and terrestrial albedo, “forcing the climate to oscillate in the same way.” Essentially Scafetta proposes tidal effects of the large gas planets influence the solar fusion process and energy distribution across the solar system, which would ultimately also result in changes in climate on our planet Earth. Considering that lunar tidal effects cause major cyclical perturbations on Earth such as tidal ebb and flow of up to 21m, the model of planetary tides influencing the solar system does not seem unreasonable.

Scafetta tested the performance of this model “against all general circulation climate models (GCMs) adopted by the IPCC (2007) to interpret climate change during the last century.” This analysis yielded a number of intriguing results. The solar scientist found “the GCMs fail to reproduce the major decadal and multi-decadal oscillations found in the global surface temperature record from 1850 to 2011,” but his harmonic model (which uses cycles having periods of 9.1, 10–10.5, 20–21 and 60–62 years) “is found to well reconstruct the observed climate oscillations from 1850 to 2011.” Scafetta also found his model “is able to forecast the climate oscillations from 1950 to 2011 using the data

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covering the period 1850–1950, and vice versa.”

Scafetta concludes the results he obtained “reinforce previous claims that the relevant physical mechanisms that explain the detected climatic cycles are still missing in the current GCMs and that climate variations at the multi-decadal scales could be astronomically induced and, in first approximation, could be forecast,” further noting “the presence of these large natural cycles can be used to correct the IPCC projected anthropogenic warming trend for the 21st century.” In doing so, he found “the temperature may not significantly increase during the next 30 years, mostly because of the negative phase of the 60-year cycle,” and IPCC-projected anthropogenic CO₂ emissions would imply a global warming of only 0.3–1.2°C by 2100, as opposed to the 1.0–3.6°C projected by the IPCC. This conclusion also would hold true if the 60-year climate cycle were a purely internal cycle (“autocycle”) originating and resonating inside the climate system without major external forcing. This model is also favored by other scientists (see for example Tsonis *et al.* 2007; Douglass 2010; Wyatt *et al.* 2012). He also has tested the CMIP5 models (Scafetta 2013a,b).

Another important synthesis of the study of the Sun-climate relation was provided by Akasofu (2010), who examined a wide range of climatic records—including temperature proxies, lake and river ice break-up dates, sea ice and sea level changes, and glaciers—to document that the current warm period is largely a natural recovery from the Little Ice Age (dated by Akasofu to be between 1200–1400 and 1800–1850). Akasofu provides evidence suggesting a relatively lower solar irradiance existed during the Little Ice Age interval.

As demonstrated in the many studies referenced above, it is fairly certain the Sun was responsible for creating multi-centennial global cold and warm periods in the past, and it is quite plausible that modern fluctuations in solar output are responsible for the majority, if not entirety, of the global warming the planet experienced during the past century or so.

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3.2 Cosmic Rays

The study of extraterrestrial climatic forcing factors is primarily a study of phenomena related to the Sun. Historically, this field of inquiry began with the work of Milankovitch (1920, 1941), who linked the cyclical glaciations of the past million years to the receipt of solar radiation at the surface of Earth as modulated by variations in Earth's orbit and rotational characteristics. Subsequent investigations implicated other solar phenomena that operate on both shorter and longer timescales. This section reviews the

findings of studies that involve galactic cosmic rays (GCRs).

The IPCC *Fifth Assessment Report* (AR5) does not consider cosmic rays as being capable of producing a significant forcing on Earth's climate. The Second Order Draft (SOD) of AR5, for example, opines "there is high confidence (medium evidence and high agreement) that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way" (p. 8.33 of the SOD of AR5, dated October 5, 2012). Furthermore, the draft claims "no robust association between changes in cosmic rays and cloudiness has been identified," while adding "in the event that such an association exists, it is very unlikely to be due to cosmic ray-induced nucleation of new aerosol particles" (p. 19 of the Technical Summary of the SOD).

By contrast, the following review of the literature clearly demonstrates the viability of GCRs as an important climate-forcing agent, where many key components of this hypothesis have been verified. The GCR theory is a growing climate forcing the IPCC must reckon with.

The field of GCR research begins with the original publication of Svensmark and Friis-Christensen (1997). A good summary can be found in the review paper of Svensmark (2007), director of the Center for Sun-Climate Research of the Danish National Space Center, who describes how he and his colleagues experimentally determined ions released to the atmosphere by galactic cosmic rays act as catalysts that significantly accelerate the formation of ultra-small clusters of sulfuric acid and water molecules that constitute the building blocks of cloud condensation nuclei. Svensmark also discusses the complex chain of expected atmospheric interactions, in particular how, during periods of greater solar activity, greater shielding of Earth occurs associated with a strong solar magnetic field. That shielding results in less cosmic rays penetrating to the lower atmosphere of the Earth, resulting in fewer cloud condensation nuclei being produced and thus fewer and less reflective low-level clouds occurring. More solar radiation is thus absorbed the surface of Earth, resulting in increasing near-surface air temperatures and global warming.

Svensmark provides support for key elements of this scenario with graphs illustrating the close correspondence between global low-cloud amount and cosmic-ray counts over the period 1984–2004. He

also notes the history of changes in the flux of galactic cosmic rays estimated since 1700, which correlates well with Earth's temperature history over the same time period, starting from the latter portion of the Maunder Minimum (1645–1715), when Svensmark says "sunspots were extremely scarce and the solar magnetic field was exceptionally weak," and continuing on through the twentieth century, over which last hundred-year interval, as noted by Svensmark, "the Sun's coronal magnetic field doubled in strength."

Svensmark also cites the work of Bond *et al.* (2001), who in studying ice-rafted debris in the North Atlantic Ocean determined, in Svensmark's words, "over the past 12,000 years, there were many icy intervals like the Little Ice Age" that "alternated with warm phases, of which the most recent were the Medieval Warm Period (roughly AD 900–1300) and the Modern Warm Period (since 1900)." As Bond's 10-member team indicates, "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."

In expanding the timescale further, while highlighting the work of Shaviv (2002, 2003a) and Shaviv and Veizer (2003), Svensmark (2007) presents plots of reconstructed sea surface temperature anomalies and relative cosmic ray flux over the past 550 million years (Svensmark's Figure 8), during which time the solar system experienced four passages through the spiral arms of the Milky Way galaxy, with the climatic data showing "rhythmic cooling of the Earth whenever the Sun crossed the galactic midplane, where cosmic rays are locally most intense." Svensmark concludes "stellar winds and magnetism are crucial factors in the origin and viability of life on wet Earth-like planets," as are "ever-changing galactic environments and star-formation rates." Shaviv (2003b) went so far as to sketch the qualitative idea for a plausible resolution of the early faint Sun paradox by arguing for a lower cosmic ray flux from a strong solar wind (i.e., more cloud coverage to keep early Earth relatively warmer than it would be otherwise) during the very early portion of Earth's 4.5 billion-year history.

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark in his overview of the cosmic ray-climate connection. Lockwood *et al.* (1999), for example, examined measurements of the near-Earth interplanetary magnetic field in an effort to determine the total magnetic flux leaving the Sun

since 1868. They showed the total magnetic flux from the Sun rose by a factor of 1.41 over the period 1964–1996, while surrogate measurements of the interplanetary magnetic field previous to this time indicate total magnetic flux had risen by a factor of 2.3 since 1901. The three researchers stated the variation in the total solar magnetic flux they found “stresses the importance of understanding the connections between the Sun’s output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field.”

In commenting on the work of Lockwood *et al.*, Parker (1999) noted additional solar considerations also may have played an important part in the modern rise of global temperature. He noted the number of sunspots doubled over the prior 100 years, and one consequence of this phenomenon would have been “a much more vigorous Sun” that was slightly brighter. Parker pointed out spacecraft measurements suggest the brightness (Br) of the Sun varies by an amount $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle. During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth century Medieval Maximum), he notes, brightness variations on the order of $\Delta Br/Br \approx 0.5\%$ typically occur. He also notes the mean temperature (T) of the northern portion of the Earth varied by 1 to 2°C in association with these variations in solar activity, stating finally, “we cannot help noting that $\Delta T/T \approx \Delta Br/Br$.” Furthermore, knowing sea surface temperatures are influenced by the brightness of the Sun and had risen since 1900, Parker writes, “one wonders to what extent the solar brightening [of the past century] has contributed to the increase in atmospheric temperature and CO₂” over that period. Parker reaches what he deems an “inescapable conclusion”: “We will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate.”

Recent findings from a Swiss team of researchers, Shapiro *et al.* (2001), indicate electromagnetic solar irradiation also probably increased much more than previously thought from the Little Ice Age until today. Based on their new study, the scientists assume an increase six times higher than the value used by the IPCC (Shapiro *et al.*, 2011; Lockwood, 2011).

Digging deeper into the cosmic ray subject, Feynman and Ruzmaikin (1999) investigated twentieth century changes in the intensity of cosmic rays incident upon Earth’s magnetopause and their

transmission through the magnetosphere to the upper troposphere. This work revealed “the intensity of cosmic rays incident on the magnetopause has decreased markedly during this century” and “the pattern of cosmic ray precipitation through the magnetosphere to the upper troposphere has also changed.”

Solanki *et al.* (2000) developed a model of the long-term evolution of the Sun’s large-scale magnetic field and compared its predictions against two proxy measures of this parameter. The model proved successful in reproducing the observed century-long doubling of the strength of the part of the Sun’s magnetic field that reaches out from the Sun’s surface into interplanetary space. It also indicated there is a direct connection between the length of the 11-year sunspot cycle and secular variations in solar activity that occur on timescales of centuries, such as the Maunder Minimum of the latter part of the seventeenth century, when sunspots were few and Earth was in the midst of the Little Ice Age.

One year later, using cosmic ray data recorded by ground-based neutron monitors, global precipitation data from the Climate Predictions Center Merged Analysis of Precipitation project, and estimates of monthly global moisture from the National Centers for Environmental Prediction reanalysis project, Kniveton and Todd (2001) set out to evaluate whether there is empirical evidence to support the hypothesis that solar variability (represented by changes in cosmic ray flux) is linked to climate change (manifested by changes in precipitation and precipitation efficiency) over the period 1979–1999. They determined there is “evidence of a statistically strong relationship between cosmic ray flux, precipitation and precipitation efficiency over ocean surfaces at mid to high latitudes,” since variations in both precipitation and precipitation efficiency for mid to high latitudes showed a close relationship in both phase and magnitude with variations in cosmic ray flux, varying 7 to 9 percent during the solar cycle of the 1980s. Other potential forcing factors were ruled out due to poorer statistical relationships.

The same year, Bond *et al.* (2001) published the results of their study of ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (¹⁰Be) and Northern Hemispheric tree rings (¹⁴C). Based on analyses of deep-sea sediment cores that yielded abundance changes in time of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern, and with the help

of an accelerator mass spectrometer date, a number of recurring alternate periods of relative cold and warmth that wended their way through the 12,000-year expanse of the Holocene. The mean duration of the several complete climatic cycles thus delineated was 1,340 years, and the two last cold and warm nodes of the latter oscillations, in the words of Bond *et al.*, were “broadly correlative with the so called ‘Little Ice Age’ and ‘Medieval Warm Period.’”

The signal accomplishment of the scientists’ study was the linking of these millennial-scale climate oscillations—and their embedded centennial-scale oscillations—with similar-scale oscillations in cosmogenic nuclide production, known to be driven by contemporaneous oscillations in solar activity. Bond *et al.* 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.” They concluded “a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic,” suggesting the cyclical climatic effects of the Sun are experienced throughout the world.

With respect to the near-global extent of the climatic impact of the solar radiation variations they detected, Bond *et al.* reference studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating “the footprint of the solar impact on climate we have documented extend[s] from polar to tropical latitudes.” They also note “the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence.” They further note their findings support previous suggestions that both the Little Ice Age and Medieval Warm Period “may have been partly or entirely linked to changes in solar irradiance.”

Bond *et al.* reiterate that the oscillations in drift-ice they studied “persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system.” At two of their coring sites, they identified a series of such cyclical variations that extended throughout all of the previous interglacial and were “strikingly similar to those of the Holocene.” Here they could also have cited the work of Oppo *et al.* (1998), who observed similar climatic oscillations in a sediment

core that covered the span of time from 340,000 to 500,000 years before present, and that of Raymo *et al.* (1998), who pushed back the time of the cycles’ earliest known occurrence to well over one million years ago.

How do the small changes in solar radiation inferred from the cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth’s global climate? Bond *et al.* describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth’s surface, provoking changes in North Atlantic deep water formation that alter the thermohaline circulation of the global ocean. They speculate “the solar signals thus may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint.” Concluding their landmark paper, the researchers write the results of their study “demonstrate that the Earth’s climate system is highly sensitive to extremely weak perturbations in the Sun’s energy output,” noting their work “supports the presumption that solar variability will continue to influence climate in the future.”

The following year, Sharma (2002) presented the case for an even longer oscillation in solar magnetism—on the order of 100,000 years—that might bear responsibility for the recurring glacial/interglacial periods. This potential finding, which has been established for only two of the putative 100,000-year cycles and could turn out to be spurious, is based upon the fact that the production of ^{10}Be in Earth’s atmosphere is affected by the intensity of magnetic activity at the surface of the Sun as well as Earth’s geomagnetic dipole strength.

Using data pertaining to these factors obtained from several different sources, Sharma began his analysis by compiling 200,000-year histories of relative geomagnetic field intensity (from natural remnant magnetizations of marine sediments) and normalized atmospheric ^{10}Be production rate (also from marine sediments). Then, with the help of a theoretical construct describing the ^{10}Be production rate as a function of the solar modulation of galactic cosmic rays (arising from variations in magnetic activity at the surface of the Sun) and Earth’s geomagnetic field intensity, he created a 200,000-year history of the solar modulation factor.

This history reveals the existence of significant periods of both enhanced and reduced solar activity; comparing it with the marine $\delta^{18}\text{O}$ record (a proxy for global ice volume and, therefore, Earth’s mean

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surface air temperature), Sharma found the two histories are strongly correlated. As he describes it, “the solar activity has a 100,000-year cycle in phase with the $\delta^{18}\text{O}$ record of glacial-interglacial cycles,” such that “the long-term solar activity and Earth’s surface temperature appear to be directly related.” Throughout the 200,000-year period, Sharma notes, “the Earth has experienced a warmer climate whenever the Sun has been magnetically more active” and “at the height of the last glacial maximum the solar activity was suppressed.” It is therefore easy for Sharma to make the final connection, setting forth as a new hypothesis the proposal that “variations in solar activity control the 100,000-year glacial-interglacial cycles,” just as they also appear to control other embedded and cascading climatic cycles.

In a contemporaneous study, Carslaw *et al.* (2002) began an essay on “Cosmic Rays, Clouds, and Climate” by noting the intensity of cosmic rays varies by about 15 percent over a solar cycle due to changes in the strength of the solar wind, which carries a weak magnetic field into the heliosphere that partially shields Earth from low-energy galactic charged particles. When this shielding is at a minimum, allowing more cosmic rays to impinge upon the planet, more low clouds have been observed to cover Earth, producing a tendency for lower temperatures to occur. When the opposite condition is true, a warmer Earth is to be expected because less low cloud cover is formed by this proposed mechanism.

The three researchers further note the total variation in low cloud amount over a solar cycle is about 1.7 percent, which corresponds to a change in the planet’s radiation budget of about one watt per square meter (1 Wm^{-2}). This change, they say, “is highly significant when compared ... with the estimated radiative forcing of 1.4 Wm^{-2} from anthropogenic CO_2 emissions.” Because of the short length of a solar cycle (11 years), the large thermal inertia of the world’s oceans dampens the much greater global temperature change that would have occurred as a result of this radiative forcing had it been spread out over a much longer period of time, so the actual observed warming is a little less than 0.1°C .

Much of Carslaw *et al.*’s review focuses on mechanisms by which cosmic rays might induce the synchronous low cloud cover changes observed to accompany changes in cosmic ray intensity. The researchers begin by briefly describing the three principal mechanisms that have been suggested to function as links between solar variability and changes in Earth’s weather: changes in total solar

irradiance that provide variable energy input to the lower atmosphere, changes in solar ultraviolet radiation and its interaction with ozone in the stratosphere that couple dynamically to the lower atmosphere, and changes in cloud processes having significance for condensation nucleus abundances, thunderstorm electrification and thermodynamics, and ice formation in cyclones.

Focusing on the third of these mechanisms, Carslaw *et al.* note cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes. They further refine their focus to concentrate on ways by which cosmic-ray-produced ions may affect cloud droplets and ice particles. Here, they concentrate on two specific topics, what they call the ion-aerosol clear-air mechanism and the ion-aerosol near-cloud mechanism. Their review suggests what we know about these subjects is very much less than what we could know about them. Many scientists, as they describe it, believe “it is inconceivable that the lower atmosphere can be globally bombarded by ionizing radiation without producing an effect on the climate system.”

Carslaw *et al.* point out cosmic ray intensity declined by about 15 percent during the past century “owing to an increase in the solar open magnetic flux by more than a factor of 2.” They further report “this 100-year change in intensity is about the same magnitude as the observed change over the last solar cycle.” In addition, it should be noted the cosmic ray intensity was already much lower at the start of the twentieth century than it was just after the start of the nineteenth century, when many historical records and climate proxies indicate the planet began its nearly two-century-long recovery from the Little Ice Age.

These observations strongly suggest solar-mediated variations in the intensity of cosmic rays bombarding Earth may indeed be responsible for the temperature variations of the past three centuries. They provide a much better fit to the temperature data than do atmospheric CO_2 data; and as Carslaw *et al.* remark, “if the cosmic ray-cloud effect is real, then these long-term changes of cosmic ray intensity could substantially influence climate.” It is this possibility, they say, that makes it “all the more important to understand the cause of the cloudiness variations,” as the cosmic ray-cloud connection may hold the key to resolving what they call this “fiercely debated geophysical phenomenon.”

One year later, and noting Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), and Palle Bago and Butler (2000) had derived

positive relationships between global cosmic ray intensity and low-cloud amount from infrared cloud data contained in the International Satellite Cloud Climatology Project (ISCCP) database for the years 1983–1993, Marsden and Lingenfelter (2003) used that database for the expanded period 1983–1999 to see if a similar relationship could be detected via cloud amount measurements made in the visible spectrum. This work revealed “a positive correlation at low altitudes, which is consistent with the positive correlation between global low clouds and cosmic ray rate seen in the infrared.”

It is appropriate here to point out there are contemporary and active disagreements within the scientific community with respect to the empirical basis for the cosmic-ray-low cloud relation originally reported by Svensmark and Friis-Christensen (1997) and in updates by colleagues. Soon *et al.* (2000) provided such a challenge to Svensmark’s empirical finding and pointed to another promising solar-weather-upper atmospheric relation involving the physico-chemical interactions of the relativistic electron precipitation events with NO_y molecules in the middle atmosphere first described in Callis *et al.* (1998). Further insights and details, as discussed in Paul Prikryl and colleagues (2009a; 2009b), involving the solar wind, aurora, and atmospheric gravity waves, also may be important in explaining physical realities and adding confidence in understanding Sun-weather-climate relations.

In 2003, Shaviv and Veizer (2003) provided additional support for a cosmic ray influence on climate, suggesting from two-thirds to three-fourths of the variance in Earth’s temperature (T) over the past 500 million years may be attributable to cosmic ray flux (CRF) variations due to solar system passages through the spiral arms of the Milky Way galaxy. They presented several half-billion-year histories of T, CRF, and atmospheric CO_2 concentrations derived from various types of proxy data and found none of the CO_2 curves showed any clear correlation with the T curves, suggesting “ CO_2 is not likely to be the principal climate driver.” By contrast, they discovered the T trends displayed a dominant cyclic component on the order of 135 ± 9 million years and “this regular pattern implies that we may be looking at a reflection of celestial phenomena in the climate history of Earth.”

That possibility is borne out by their identification of a similar CRF cycle of 143 ± 10 million years, together with the fact that the large cold intervals in the T records “appear to coincide with

times of high CRF,” a correspondence that would be expected from the likely chain of events: high CRF $\implies$ more low-level clouds $\implies$ greater planetary albedo $\implies$ colder climate, as described by Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), Palle Bago and Butler (2000), and Marsden and Lingenfelter (2003).

What do these findings suggest about the role of atmospheric CO_2 variations with respect to global temperature change? Shaviv and Veizer begin their analysis by stating the conservative approach is to assume the entire residual variance not explained by measurement error is due to CO_2 variations. Doing so, they found a doubling of the air’s CO_2 concentration could account for only about a 0.5°C increase in T. This result differs considerably, in their words, “from the predictions of the general circulation models, which typically imply a CO_2 doubling effect of $\sim 1.5\text{--}5.5^\circ\text{C}$ ” but is “consistent with alternative lower estimates of $0.6\text{--}1.6^\circ\text{C}$ (Lindzen, 1997).” Shaviv and Veizer’s result is even more consistent with the results of the eight empirically based “natural experiments” of Idso (1998), which yield an average warming of about 0.4°C for a 300 to 600 ppm doubling of the atmosphere’s CO_2 concentration.

In another important test of a critical portion of the cosmic ray-climate connection theory, Usoskin *et al.* (2004b) compared the spatial distributions of low cloud amount (LCA) and cosmic ray-induced ionization (CRII) over the globe for the period 1984–2000. They used observed LCA data from the ISCCP-D2 database limited to infrared radiances and employed CRII values calculated by Usoskin *et al.* (2004a) at 3 km altitude, which corresponds roughly to the limiting altitude below which low clouds form. This work revealed “the LCA time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting a clear 11-year cycle in phase with CRII.” In addition, they found “a one-to-one relation between the relative variations of LCA and CRII over the latitude range $20\text{--}55^\circ\text{S}$ and $10\text{--}70^\circ\text{N}$ ” and “the amplitude of relative variations in LCA was found to increase polewards, in accordance with the amplitude of CRII variations.” These findings of the five-member team of Finnish, Danish, and Russian scientists provide substantial evidence for a solar-cosmic ray linkage (the 11-year cycle of CRII) and a cosmic ray-cloud linkage (the in-phase cycles of CRII and CLA), making the full solar activity/cosmic ray/low cloud/climate change hypothesis appear to be rather robust.

In a review of the temporal variability of solar

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phenomena, Lean (2005) made an important but disturbing point about climate models and the Sun-climate connection: “A major enigma is that general circulation climate models predict an immutable climate in response to decadal solar variability, whereas surface temperatures, cloud cover, drought, rainfall, tropical cyclones, and forest fires show a definite correlation with solar activity (Haigh, 2001, Rind, 2002).”

Lean begins her review by noting the beginning of the Little Ice Age “coincided with anomalously low solar activity (the so-called Sporer and Maunder minima)” and “the latter part coincided with both low solar activity (the Dalton minimum) and volcanic eruptions.” After discussing the complexities of this potential relationship, she considers another alternative: “Or might the Little Ice Age be simply the most recent cool episode of millennial climate-oscillation cycles?” Lean cites evidence revealing the sensitivity of drought and rainfall to solar variability, stating climate models are unable to reproduce what she called the “plethora” of Sun-climate connections. She notes simulations with climate models yield decadal and centennial variability even in the absence of external forcing, stating “arguably, this very sensitivity of the climate system to unforced oscillation and stochastic noise predisposes it to nonlinear responses to small forcings such as by the Sun.”

Lean reports “various high-resolution paleoclimate records in ice cores, tree rings, lake and ocean sediment cores, and corals suggest that changes in the energy output of the Sun itself may have contributed to Sun-Earth system variability,” citing the work of Verschuren *et al.* (2000), Hodel *et al.* (2001), and Bond *et al.* (2001). She notes “many geographically diverse records of past climate are coherent over time, with periods near 2,400, 208, and 90 years that are also present in the ^{14}C and ^{10}Be archives,” as these isotopes (produced at the end of a complex chain of interactions initiated by galactic cosmic rays) contain information about various aspects of solar activity (Bard *et al.*, 1997).

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. Their 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.

By contrast, 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 data sets at time scales from approximately 10 to 100 years.

These results 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. 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. Although scientists lack a complete understanding of many solar/GCR-induced climatic influences, this study highlights the growing need for such relationships to be explored. As it and others have shown, small changes in solar output can indeed induce significant changes in Earth’s climate.

More recent analyses by Veretenenko and Ogurtsov (2012) and Georgieva *et al.* (2012) have added details to the intricate relationship between solar-cosmic-ray activity, plausibly mediated by geomagnetic activity, and weather-climate circulation patterns around the North Atlantic and elsewhere. Veretenenko and Ogurtsov (2012) emphasize the 60-year periodicity in some of the sun-climate relationship, while Georgieva *et al.* (2012) worked toward an explanation of the occasional time-dependence of the statistical correlations between solar and climatic variables.

Also working in the North Atlantic region, Macklin *et al.* (2005) developed what they call “the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ^{14}C -dated British flood deposits,” after which 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 have 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 find “an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ^{14}C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods.”

Usoskin *et al.* (2005) note “the variation of the cosmic ray flux entering Earth’s atmosphere is due to a combination of solar modulation and geomagnetic shielding, the latter adding a long-term trend to the varying solar signal.” They also note “the existence of a geomagnetic signal in the climate data would support a direct effect of cosmic rays on climate.” They evaluate this proposition by reproducing 1,000-year reconstructions of two notable solar-heliospheric indices derived from cosmogenic isotope data—the sunspot number and the cosmic ray flux (Usoskin *et al.*, 2003; Solanki *et al.*, 2004)—and creating a new 1,000-year air temperature history of the Northern Hemisphere by computing annual means of six different thousand-year surface air temperature series—those of Jones *et al.* (1998), Mann *et al.* (1999), Briffa (2000), Crowley (2000), Esper *et al.* (2002), and Mann and Jones (2003). In comparing these three series (solar activity, cosmic ray flux, and air temperature), Usoskin *et al.* found they “indicate higher temperatures during times of more intense solar activity (higher sunspot number, lower cosmic ray flux).” In addition, they report three different statistical tests “consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with sunspots,” suggesting something in addition to solar activity must have been influencing the cosmic ray flux in order to make the flux the better correlate of temperature.

Noting Earth’s geomagnetic field strength would be a natural candidate for this “something,” Usoskin *et al.* compared their solar activity, cosmic ray, and temperature reconstructions with two long-term reconstructions of geomagnetic dipole moment obtained from the work of Hongre *et al.* (1998) and Yang *et al.* (2000). This effort revealed that between AD 1000 and 1700, when there was a substantial downward trend in air temperature associated with a less substantial downward trend in solar activity, there was also a general downward trend in geomagnetic field strength. Usoskin *et al.* suggested the substantial upward trend of cosmic ray flux needed to sustain the substantial rate of observed

cooling (which was more than expected in light of the slow decline in solar activity) was likely due to the positive effect on the cosmic ray flux produced by the decreasing geomagnetic field strength.

After 1700, the geomagnetic field strength continued to decline, but air temperature began to rise. This “parting of company” between the two parameters, according to Usoskin *et al.*, occurred because “the strong upward trend of solar activity during that time overcompensate[d] [for] the geomagnetic effect,” leading to a significant warming. In addition, some of the warming of the past century or so (15–20 percent) may have been caused by the concomitant increase in the atmosphere’s CO_2 content, which would have complemented the warming produced by the solar activity and further decoupled the upward trending temperature from the declining geomagnetic field strength.

Together, these observations tend to strengthen the hypothesis that cosmic ray variability was a significant driver of changes in Earth’s surface air temperature over the past millennium, and that this forcing was driven primarily by variations in solar activity modulated by the more slowly changing geomagnetic field strength of the planet, which sometimes strengthened the solar forcing and sometimes worked against it. The results leave room for only a small impact of anthropogenic CO_2 emissions on twentieth century warming.

Versteegh (2005) reviewed what was known about past climatic responses to solar forcing and their geographical coherence based upon proxy records of temperature and the cosmogenic radionuclides ^{10}Be and ^{14}C , which provide a measure of magnetized plasma emissions from the Sun that affect Earth’s exposure to galactic cosmic rays. Versteegh concluded “proxy records provide ample evidence for climate change during the relatively stable and warm Holocene” and “all frequency components attributed to solar variability re-occur in proxy records of environmental change.” The author emphasized “the ~90 years Gleisberg and ~200 years Suess cycles in the ^{10}Be and ^{14}C records” as well as “the ~1500 years Bond cycle which occurs in several proxy records [and] could originate from the interference between centennial-band solar cycles.” Versteegh concludes “long-term climate change during the preindustrial [era] seems to have been dominated by solar forcing,” and the long-term response to solar forcing “greatly exceeds unforced variability.”

Harrison and Stephenson (2005) note that because the net global effect of clouds is cooling (Hartman, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF), measured daily at 0900 UT at Whiteknights, Reading (UK) from 1997–2004, with the traditional subjective determination of cloud amount made by a human observer as well as with daily average temperature. They compared the diffuse fraction measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux. They report, “across the UK, on days of high cosmic ray flux (which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by $19\% \pm 4\%$, and (ii) the diffuse fraction increases by $2\% \pm 0.3\%$.” In addition, they found “during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction.”

The two researchers note the last of these observations indicates diffuse radiation changes are “unambiguously due to cosmic rays.” They also report, “at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR.” Consequently, they suggest the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima, and “this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al.*, 2003) which neglect a cosmic ray effect.” In addition, although the effect they detect is small, they say it is “statistically robust” and the cosmic ray effect on clouds likely “will emerge on long time scales with less variability than the considerable variability of daily cloudiness.”

Based on information that indicated a solar activity-induced increase in radiative forcing of 1.3 Wm^{-2} over the twentieth century (by way of cosmic ray flux reduction), plus the work of others (Hoyt and Schatten, 1993; Lean *et al.*, 1995; Solanki and Fligge, 1998) that indicated a globally averaged solar luminosity increase of approximately 0.4 Wm^{-2} over the same period, Shaviv (2005) calculated an overall and ultimately solar activity-induced warming of 0.47°C ($1.7 \text{ Wm}^{-2} \times 0.28^\circ\text{C per Wm}^{-2}$) over the twentieth century. Added to the 0.14°C of

anthropogenic-induced warming, the calculated total warming of the twentieth century thus came to 0.61°C , noted by Shaviv to be very close to the 0.57°C temperature increase said by the IPCC to have been observed over the past century. Both Shaviv’s and Idso’s analyses, which mesh well with real-world data of both the recent and distant past, suggest only 15 to 20 percent ($0.10^\circ\text{C}/0.57^\circ\text{C}$) of the observed warming of the twentieth century can be attributed to the rise in the air’s CO_2 content.

In another study from 2005, de Jager (2005) reviewed what was known at the time about the role of the Sun in orchestrating climate change over the current interglacial period, including changes that occurred during the twentieth century, focusing on the direct effects of solar irradiance variations and the indirect effects of magnetized plasma emissions.

With respect to solar irradiance variations, de Jager writes, “the fraction of the solar irradiance that directly reaches the Earth’s troposphere is emitted by the solar photosphere [and] does not significantly vary.” The variable part of this energy flux, as he continues, is emitted by chromospheric parts of centers of solar activity and “only directly influences the higher, stratospheric terrestrial layers,” which “can only influence the troposphere by some form of stratosphere-troposphere coupling.” With respect to magnetized plasma emissions, de Jager concludes “the outflow of magnetized plasma from the Sun and its confinement in the heliosphere influences the Earth’s environment by modulating the flux of galactic cosmic radiation observed on Earth.” He notes “cosmogenic radionuclides are proxies for this influence” and “the variable cosmic ray flux may influence climate via variable cloudiness.”

Of these two phenomena, deJager seems to lean toward the latter as being the more significant. He notes the Northern Hemispheric temperature history developed by Moberg *et al.* (2005) “runs reasonably well parallel to” reconstructions of past solar variability derived from cosmogenic radionuclide concentrations, which are proxies for the outflow of magnetized plasma from the Sun. Perhaps most interesting in this regard is de Jager’s observation that “never during the past ten or eleven millennia has the Sun been as active in ejecting magnetized plasma as during the second half of the twentieth century.”

de Jager notes “a topical and much debated question is that of the cause of the strong terrestrial heating in the last few decades of the twentieth century,” which “is usually ascribed to greenhouse warming.” His review gives credence to the view that

solar activity, especially that associated with the effects of ejected magnetized plasma on the galactic cosmic ray flux incident on Earth's atmosphere, could be responsible for the bulk of twentieth century warming as well as most of the major temperature swings (both up and down) of the Holocene.

Usoskin *et al.* (2006) say many solar scientists believe changes in solar activity have been responsible for significant changes in climate, but to demonstrate that a record of past variations in solar activity is required. They note "long-term solar activity in the past is usually estimated from cosmogenic isotopes, ^{10}Be or ^{14}C , deposited in terrestrial archives such as ice cores and tree rings," because "the production rate of cosmogenic isotopes in the atmosphere is related to the cosmic ray flux impinging on Earth," which "is modulated by the heliospheric magnetic field and is thus a proxy of solar activity." A nagging concern, however, is that the isotope records may suffer from what the five scientists call "uncertainties due to the sensitivity of the data to several terrestrial processes."

Noting the activity of a cosmogenic isotope in a meteorite represents "the time integrated cosmic ray flux over a period determined by the mean life of the radioisotope," Usoskin *et al.* reasoned "by measuring abundance of cosmogenic isotopes in meteorites which fell through the ages, one can evaluate the variability of the cosmic ray flux, since the production of cosmogenic isotopes ceases after the fall of the meteorite." If they could develop such a meteoritic-based cosmogenic isotope record, they posit, they could use it "to constrain [other] solar activity reconstructions using cosmogenic ^{44}Ti activity in meteorites which is not affected by terrestrial processes."

The researchers chose ^{44}Ti for this purpose because it has a half-life of about 59 years and is thus "relatively insensitive to variations of the cosmic ray flux on decadal or shorter time scales but is very sensitive to the level of the cosmic ray flux and its variations on a centennial scale." They compared the results of different long-term ^{10}Be - and ^{14}C -based solar activity reconstruction models with measurements of ^{44}Ti in 19 stony meteorites (chondrites) that fell between 1766 and 2001, as reported by Taricco *et al.* (2006). They determined "most recent reconstructions of solar activity, in particular those based on ^{10}Be data in polar ice (Usoskin *et al.*, 2003, 2004c; McCracken *et al.*, 2004) and on ^{14}C in tree rings (Solanki *et al.*, 2004), are consistent with the ^{44}Ti data."

Dergachev *et al.* (2006) reviewed "direct and indirect data on variations in cosmic rays, solar activity, geomagnetic dipole moment, and climate from the present to 10–12 thousand years ago, [as] registered in different natural archives (tree rings, ice layers, etc.)." They found "galactic cosmic ray levels in the Earth's atmosphere are inversely related to the strength of the helio- and geomagnetic fields" and conclude "cosmic ray flux variations are apparently the most effective natural factor of climate changes on a large time scale." They note "changes in cloud processes under the action of cosmic rays, which are of importance for abundance of condensation nuclei and for ice formation in cyclones, can act as a connecting link between solar variability and changes in weather and climate." They cite numerous scientific studies indicating "cosmic rays are a substantial factor affecting weather and climate on time scales of hundreds to thousands of years."

Noting "there is evidence that solar activity variations can affect the cloud cover at Earth" but "it is still unclear which solar driver plays the most important role in the cloud formation," Voiculescu *et al.* (2006) used "partial correlations to distinguish between the effects of two solar drivers (cosmic rays and the UV irradiance) and the mutual relations between clouds at different altitudes." They found "a strong solar signal in the cloud cover," noting "low clouds are mostly affected by UV irradiance over oceans and dry continental areas and by cosmic rays over some mid-high latitude oceanic areas and moist lands with high aerosol concentration." They further state "high clouds respond more strongly to cosmic ray variations, especially over oceans and moist continental areas."

Gallet and Genevey (2007) documented what they call a "good temporal coincidence" between "periods of geomagnetic field intensity increases and cooling events" as measured in western Europe, where cooling events were "marked by glacier advances on land and increases in ice-rafted debris in [North Atlantic] deep-sea sediments." Their analyses revealed "a succession of three cooling periods in western Europe during the first millennium AD," the ages of which were "remarkably coincident with those of the main discontinuities in the history of Maya civilization," confirming the earlier work of Gallet *et al.* (2005), who had found a "good temporal coincidence in western Europe between cooling events recovered from successive advances of Swiss glaciers over the past 3,000 years and periods of rapid increases in geomagnetic field intensity," the latter of

which were “nearly coeval with abrupt changes, or hairpin turns, in magnetic field direction.”

Gallet and Genevey concluded “the most plausible mechanism linking geomagnetic field and climate remains a geomagnetic impact on cloud cover,” whereby “variations in morphology of the Earth’s magnetic field could have modulated the cosmic ray flux interacting with the atmosphere, modifying the nucleation rate of clouds and thus the albedo and Earth surface temperatures (Gallet *et al.*, 2005; Courtillot *et al.*, 2007).” These observations clearly suggest a global impact on climate, which is further suggested by the close relationship found to exist between “cooling periods in the North Atlantic and aridity episodes in the Middle East,” as well as by the similar relationship demonstrated by Gallet and Genevey to have prevailed between periods of aridity over the Yucatan Peninsula and well-documented times of crisis in Mayan civilization.

In another study that took a look at the really big picture, painted by rhythmically interbedded limestone and shale or limestone and chert known as *rhythmites*, Elrick and Hinnov (2007) “(1) review the persistent and widespread occurrence of Palaeozoic *rhythmites* across North America, (2) demonstrate their primary depositional origin at millennial time scales, (3) summarize the range of paleo-environmental conditions that prevailed during *rhythmite* accumulation, and (4) briefly discuss the implications primary Palaeozoic *rhythmites* have on understanding the origin of pervasive late Neogene-Quaternary millennial-scale climate variability.” They conclude “millennial-scale climate changes occurred over a very wide spectrum of paleoceanographic, paleogeographic, paleoclimatic, tectonic, and biologic conditions and over time periods from the Cambrian to the Quaternary.” Given these observations, they note, “it is difficult to invoke models of internally driven thermohaline oceanic oscillations or continental ice sheet instabilities to explain their origin.” Consequently, they suggest “millennial-scale paleoclimate variability is a more permanent feature of the Earth’s ocean-atmosphere system, which points to an external driver such as solar forcing.”

Kirkby (2008) reports “diverse reconstructions of past climate change have revealed clear associations with cosmic ray variations recorded in cosmogenic isotope archives, providing persuasive evidence for solar or cosmic ray forcing of the climate.” He discusses two classes of microphysical mechanisms that have been proposed to connect cosmic rays with clouds, which interact significantly with fluxes of

both solar and thermal radiation and, therefore, climate: “firstly, an influence of cosmic rays on the production of cloud condensation nuclei and, secondly, an influence of cosmic rays on the global electrical circuit in the atmosphere and, in turn, on ice nucleation and other cloud microphysical processes.”

Kirkby observes “considerable progress on understanding ion-aerosol-cloud processes has been made in recent years, and the results are suggestive of a physically plausible link between cosmic rays, clouds and climate.” “With new experiments planned or underway, such as the CLOUD facility at CERN,” he states, “there are good prospects that we will have some firm answers to this question within the next few years.” He points out, “the question of whether, and to what extent, the climate is influenced by solar and cosmic ray variability remains central to our understanding of the anthropogenic contribution to present climate change.”

In another paper published the same year, Shaviv (2008) notes “climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales,” citing numerous references. Nevertheless, it has been difficult for the IPCC to accept the logical derivative of this fact, that solar variations are driving major climate changes. The IPCC contends measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes. The dilemma might be resolved if some amplification mechanism were discovered, but most attempts to do so 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 to 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 “to consistently derive the same oceanic heat flux.” He demonstrated “there are large variations in the oceanic heat content together with the 11-year solar cycle” and reports the three independent data sets “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.”

Finding it difficult to resist pointing, however, Shaviv acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis, which was suggested by Ney (1959), discussed by Dickinson (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 concludes the solar-wind modulated CRF hypothesis is “a favorable candidate” for primary instigator of the many climatic phenomena discussed in this chapter.

Knudsen and Riisager (2009), while noting “the galactic cosmic ray (GCR) flux is also modulated by Earth’s magnetic field,” state “if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between Earth’s magnetic field and climate.” In a test of this supposition, Knudsen and Riisager set out to “compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen *et al.*, 2008) with proxy records for past low-latitude precipitation (Fleitman *et al.*, 2003; Wang *et al.*, 2005).” The first of these proxy records is derived from a speleothem $\delta^{18}\text{O}$ record obtained from stalagmite Q5 from Qunf cave in southern Oman, and the second is derived from a similar record obtained from stalagmite DA from Dongge cave in southern China.

The two researchers say the various correlations they observed over the course of the Holocene “suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment.” They note the general increase in precipitation observed over the past 1,500 years in both speleothem records “cannot be readily explained by changes in summer insolation or solar activity” but “correlates very well with the rapid decrease in dipole moment observed during this period.” This relationship is explained by the fact that “a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation.” Knudsen and Riisager conclude, “in addition to supporting the notion that variations in the geomagnetic field may

have influenced Earth’s climate in the past,” their study also provides support for a link “between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system.”

Concurrently, Ram *et al.* (2009) focused their attention on studies of dust in the Greenland Ice Sheet Project 2, acknowledging others have shown the dust concentration in the upper 2.8 km of the ice, spanning approximately 100,000 years, “is strongly modulated at regular periods close to 11, 22, 80 and 200 years, all of which are well-known periods of solar activity” (Ram *et al.*, 1998; Ram and Stolz, 1999). But they concede “an amplifying mechanism must be at work if solar influence is to be taken seriously.” They go on to describe work that largely satisfies that criterion as it applies to dust variability, indicating “changes in nucleation processes in clouds associated with the cosmic ray flux (CRF) can provide the necessary amplification,” which they describe in abbreviated form as “increased solar activity $\rightarrow$ decreased cosmic ray flux $\rightarrow$ decreased air-Earth [downward electric] current [density (J_z)] $\rightarrow$ decreased contact nucleation $\rightarrow$ decreased precipitation $\rightarrow$ increased dust.”

Since this chain of events operates via changes in cloud characteristics, Ram *et al.* (2009) conclude it provides “circumstantial evidence for a Sun/climate connection mediated by the terrestrial CRF,” which “may initiate a sufficiently large amplification mechanism that can magnify the influence of the Sun on the Earth’s climate beyond the traditional radiative effects.” They encourage additional work to “incorporate the effects of the CRF on J_z (and associated nucleation processes), and the subsequent microphysical responses, into macroscopic cloud models that can then be incorporated into global climate models.” Until this is done successfully, today’s climate models cannot be claimed to include all processes that may be of significance to the accurate simulation of Earth’s future climate. The importance of the global electric circuit for connecting the electrically induced changes in cloud microphysics and storm vorticity, as well as plausible effects on large-scale circulation, is spelled out by Tinsley and colleagues (see Tinsley *et al.* 2007; Tinsley 2012).

Henrik Svensmark and two coauthors (Svensmark *et al.* 2009), all from the National Space Institute of the Technical University of Denmark in Copenhagen, explored the consequences of Forbush decreases (FDs) in the influx of galactic cosmic rays (GCRs)

produced by periodic explosive events on the Sun that result in “magnetic plasma clouds from solar coronal mass ejections that pass near the Earth and provide a temporary shield against GCRs.” Based on cloud liquid water content data obtained over the world’s oceans by the Special Sounder Microwave Imager, liquid water cloud fraction data obtained by the Moderate Resolution Imaging Spectroradiometer, and data on IR detection of low clouds over the ocean by the International Satellite Cloud Climate Project, as well as FD data obtained from 130 neutron monitors world-wide and the Nagoya muon detector, Svensmark *et al.* found “substantial declines in liquid-water clouds, apparently tracking the declining cosmic rays and reaching minima some [~7] days after the GCR minima.” Concurrently, they also found “parallel observations by the aerosol robotic network AERONET reveal falls in the relative abundance of fine aerosol particles, which, in normal circumstances, could have evolved into cloud condensation nuclei.”

The Danish scientists say their results “show global-scale evidence of conspicuous influences of solar variability on cloudiness and aerosols.” They report “the loss of ions from the air during FDs reduces the cloud liquid water content over the oceans” and note “so marked was the response to relatively small variations in the total ionization” that “a large fraction of Earth’s clouds could be controlled by ionization.” Such observations support Svensmark’s theory that solar-activity-induced decreases in GCR bombardment of Earth lead to decreases in low (<3.2 km) clouds as a result of reduced atmospheric ionization and, therefore, less fine aerosol particles that under normal circumstances could have evolved into cloud condensation nuclei that could have resulted in more low-level clouds that could have cooled the planet.

Voiculescu and Usoskin (2012) offered some guidelines for the study of solar-GCR-cloud relation: “A consensus regarding the impact of solar variability on cloud cover is far from being reached,” they note. “Our results show that solar signatures in cloud cover persist in some key climate-defining regions for the entire time period [i.e., 1984–2009] and supports the idea that, if existing, solar effects are not visible at the global level and any analysis of solar effects on cloud cover (and consequently, on climate) should be done at the regional level.”

Le Mouel *et al.* (2010a) examined the Sun-climate connection on a much-reduced time scale. The team of Professors Jean-Louis Le Mouel, Vincent

Courtillot, and colleagues has published several papers investigating how the Sun’s variable magnetic activity may affect various terrestrial phenomena, including weather and climate (see for example Kossobokov *et al.* 2010; Le Mouel *et al.* 2010b). Their 2010 publication (Le Mouel *et al.* 2010a) adds insight to the topic.

Figure 3.2.1, for example, displays unexpected and surprising correlations between the long-term variation in the amplitude (A) of the solid Earth rotation parameter (here they have adopted its well-detected semiannual variation) called length of day, and two candidate solar activity measures: sunspot number (SN) and neutron count (NC, a proxy for incoming galactic cosmic rays), obtained from a station in Moscow, Russia. They point out A and NC are inversely correlated with SN, the solar activity index, which leads A by about one year. And since galactic cosmic rays are also inversely related to sunspot number with a delay of one to two years or so, A is directly correlated to NC.

Le Mouel *et al.* explain the correlations as being due to a plausible physical link of the 11-year solar activity cycle to a systematic modulation of tropospheric zonal wind, since winds above 30 km contribute less than 20 percent of Earth’s angular momentum, as proxied by A.

They also point out that, although the IPCC and others usually rule out the role of solar irradiance impact on terrestrial climate because of the small interannual changes in the solar irradiance, such an argument does not apply to the plausible link of the large seasonal incoming solar radiation in modulating the semiannual oscillations in the length-of-day amplitude. Le Mouel *et al.* say their paper “shows that the Sun can (directly or indirectly) influence tropospheric zonal mean-winds over decadal to multidecadal time scales.” And noting “zonal mean-winds constitute an important element of global atmospheric circulation,” they go on to suggest, “if the solar cycle can influence zonal mean-winds, then it may affect other features of global climate as well, including oscillations such as the NAO (North Atlantic Oscillation) and MJO (Madden-Julian Oscillation), of which zonal winds are an ingredient.” Thus, “the cause of this forcing,” as they describe it, “likely involves some combination of solar wind, galactic cosmic rays, ionosphere-Earth currents and cloud microphysics.”

Takahashi *et al.* (2010) found evidence for ~27 day variation in the Outgoing Longwave Radiation data record (a proxy of cloud amount) in

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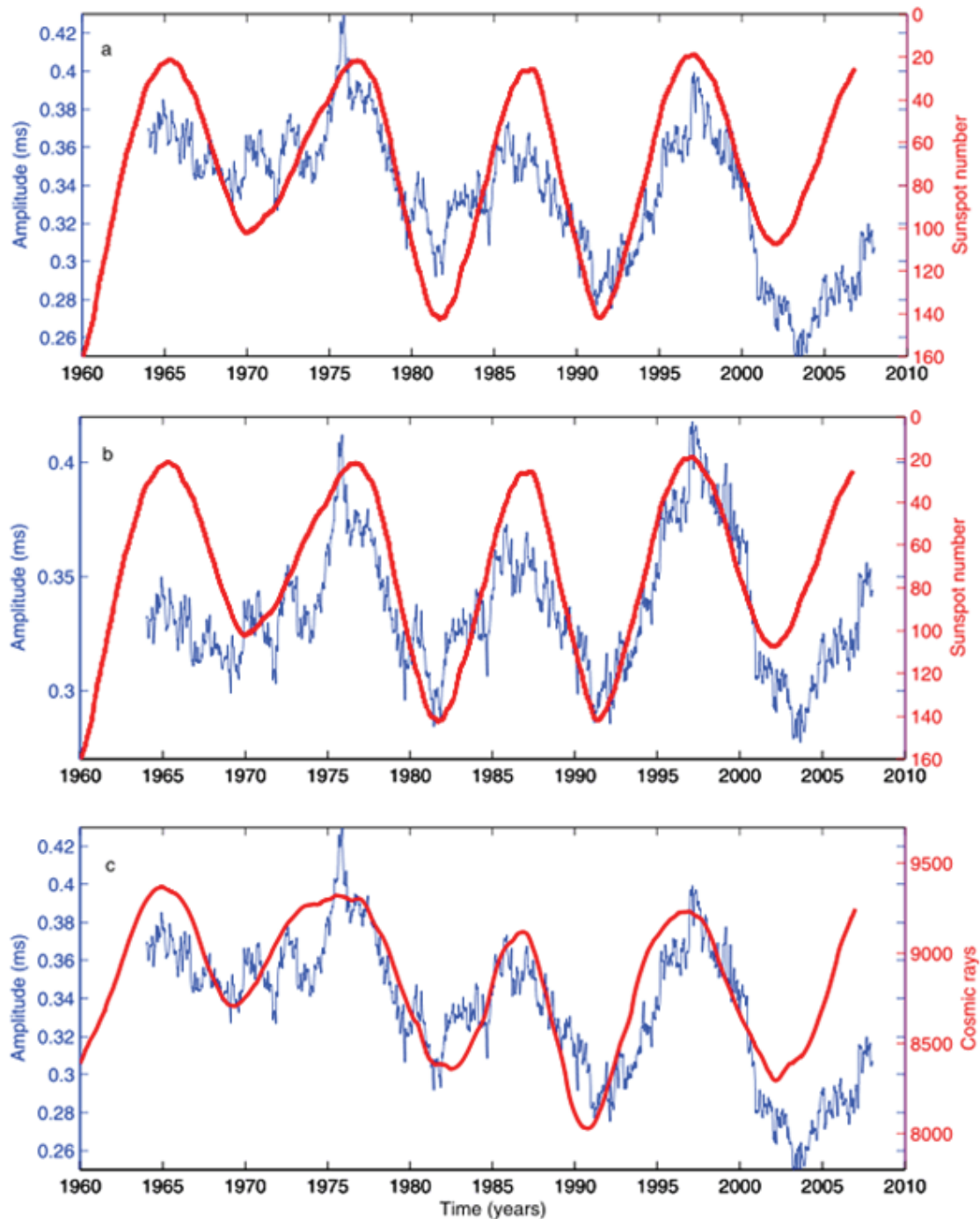


Figure 3.2.1. Correlation between the amplitude of the semiannual oscillation in length of day (blue curves with middle panel as detrended data with both top and bottom panels as original data) and various solar activity measures (sunspot numbers and proxy for galactic cosmic rays: red curves) from 1962–2009. A four-year moving-average filter was used to smooth the data series. Reprinted with permission from Le Mouél, J.-L., Kossobokov, V., and Courtillot, V. 2010b. A solar pattern in the longest temperature series from three stations in Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* 72: 62–76.

the Western Pacific warm pool region during solar activity maximum years. A significant enhancement

is also found in the period of 40–60 days, corresponding to the MJO periods. A follow-up study

by Hong *et al.* (2011) found further complexity in the relationship by showing the dependence of the correlations of solar rotation activity to the cloud amount on the phase of the QBO equatorial stratospheric winds. The team of Le Mouel and Courtillot follow up with the demonstration of the modulation of the MJO periods by 11-yr-like solar activity adopting both the solar UV and GCR proxies in Blanter *et al.* (2012).

Contemporaneously, Scafetta (2010) investigated less-explored solar-planetary interactions and how they might also be capable of influencing Earth's climate. Using the pattern of perturbations of the Sun's motion relative to the center of the solar system as a measure of the internal gravitational interactions of the Sun-planet system, he identified—via spectral analysis and other means—a number of clear periodic signals. A spectral decomposition of Hadley Centre climate data shows similar spectra, with the results of a spectral coherence test of the two histories being highly significant. The spectral pattern of climate model simulations does not match the solar and climatic variability patterns, whereas the output of a model based on astronomically forced cycles matches global temperature data well, and it matches ocean temperature data even better.

The mechanism behind the newly discovered suite of relationships appears to be a combination of planetary gravitational effects upon the Sun (see Scafetta 2012a,b; Scafetta and Willson, 2013a,b) that influence both direct solar irradiance and the Sun's magnetic field, plus an interaction of the magnetic fields of the other planets with Earth's magnetic field and the solar wind. Through these means the solar-terrestrial magnetic field experiences oscillations of several different frequencies, each of which exerts an influence on the intensity of cosmic rays reaching Earth and the subsequent generation of climate-changing clouds.

Two recent works by Abreu *et al.* (2012) and McCracken *et al.* (2013) reported on the interesting co-occurrences of periodic variations in the empirical solar modulation parameter (deduced from ^{14}C and ^{10}Be) and theoretical calculation of the planet-induced torque on the assumed aspherical shell of the solar tachocline. The remarkable coincidence of the five periodic changes on timescales of 88, 104, 150, 208, and 506 years should encourage further scientific investigation to find the true and correct physical mechanisms in order to explain and confirm how both the gaseous giant planets and inner terrestrial planets of our solar system together could influence the

internal operation of the solar magnetic dynamo within the Sun and therefore its radiative and magnetic outputs.

One promising possibility has been proposed by Wolff and Patrone (2010), who described how the inertial motions of the Sun with respect to the barycenter of the solar system may be linked to the inner working of the solar dynamo. Wolff and Patrone also show how the orbital angular momentum of the solar inertial motion can lead to storage (and subsequent release) of potential energy within the inner solar shell through differential exchanges of mass or fluid element within the inner Sun.

The important dynamical characterization and link of the plausible planetary influences and modulations on the long-term operation of the internal solar dynamo was recently highlighted by Cionco and Campagnucci (2012). In addition, McCracken *et al.* (2013) confirm the periodic changes in millennial timescale over the past 9,400 years.

In light of the evidence presented above, the flux of galactic cosmic rays clearly wields an important influence on Earth's climate, likely much more so than that exhibited by the modern increase in atmospheric CO_2 . That makes fluctuations in the Sun the primary candidate for “prime determinant” of Earth's climatic state. At the very least, these research findings invalidate the IPCC's AR5 claim that “there is high confidence (medium evidence and high agreement) that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way” (p. 8.33 of the SOD of AR5, dated October 5, 2012) and that “no robust association between changes in cosmic rays and cloudiness has been identified” (p. 19 of the Technical Summary of the SOD).

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3.3 Temperature

This section examines correlations between various solar indices and temperature across the globe and for various sub-regions of the planet. These findings suggest a much larger influence of the Sun on climate forcing than is acknowledged by the IPCC. For example, mutual analysis of daily total solar irradiance (TSI) and various air temperature time series reveals important statistical variability structure common to both the solar forcing and the climate system response series. Because the length of analyzed series reaches climate scale, the result can improve our understanding about climate variability.

3.3.1 Global

The claim that anthropogenic greenhouse gas emissions have been responsible for twentieth century warming is based on what Loehle (2004) calls “the standard assumption in climate research, including the IPCC reports,” that “over a century time interval there is not likely to be any recognizable trend to global temperatures (Risbey *et al.*, 2000), and thus the null model for climate signal detection is a flat temperature trend with some autocorrelated noise.” Loehle continues, “any warming trends in excess of that expected from normal climatic variability are then assumed to be due to anthropogenic effects.” That assumption misses the possibility of significant underlying climate trends or cycles.

Loehle used a pair of 3,000-year proxy climate records with minimal dating errors to characterize the pattern of climate change over the past three millennia simply as a function of time, with no attempt to make the models functions of solar activity or any other physical variable. The first of the two temperature series was the sea surface temperature (SST) record of the Sargasso Sea, derived by Keigwin

(1996) from a study of the oxygen isotope ratios of foraminifera and other organisms contained in a sediment core retrieved from a deep-ocean drilling site on the Bermuda Rise. This record provides SST data for about every 67th year from 1125 BC to 1975 AD. The second temperature series was the ground surface temperature record derived by Holmgren *et al.* (1999, 2001) from studies of stalagmites found in a cave in South Africa, with color variations caused by changes in the concentrations of humic materials entering the region's ground water that were reliably correlated with regional near-surface air temperature.

Loehle used these two specific records because “most other long-term records have large dating errors, are based on tree rings, which are not reliable for this purpose (Broecker, 2001), or are too short for estimating long-term cyclic components of climate.” Also, in a repudiation of the approach employed by Mann *et al.* (1998, 1999) and Mann and Jones (2003), he reports “synthetic series consisting of hemispheric or global mean temperatures are not suitable for such an analysis because of the inconsistent timescales in the various data sets,” noting further, as a result of his own testing, “when dating errors are present in a series, and several series are combined, the result is a smearing of the signal.”

Can only two temperature series reveal the pattern of global temperature change? According to Loehle, “a comparison of the Sargasso and South Africa series shows some remarkable similarities of pattern, especially considering the distance separating the two locations,” suggesting “the climate signal reflects some global pattern rather than being a regional signal only.” He also notes a comparison of the mean record with the South Africa and Sargasso series from which it was derived “shows excellent agreement” and “the patterns match closely.” He notes “this would not be the case if the two series were independent or random.”

Loehle fits seven time-series models to the two temperature series and to the average of the two series, using no data from the twentieth century. In all seven cases, good to excellent fits were obtained. As one example, the three-cycle model he fit to the averaged temperature series had a simple correlation of 0.58 and an 83 percent correspondence of peaks when evaluated by a moving window count.

Comparing the forward projections of the seven models through the twentieth century, Loehle notes six of the models “show a warming trend over the 20th century similar in timing and magnitude to the Northern Hemisphere instrumental series,” and “one

of the models passes right through the 20th century data.” Such results suggest “20th century warming trends are plausibly a continuation of past climate patterns” and, therefore, that “anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes.”

Loehle's analyses also reveal a long-term linear cooling trend of 0.25°C per thousand years since the peak of the interglacial warm period that occurred some 7,000 years ago, essentially identical to the mean value of the trend derived from seven prior assessments of its magnitude and five prior climate reconstructions. In addition, Loehle's analyses reveal the existence of the Medieval Warm Period of 800–1200 AD, which was shown to have been significantly warmer than the Current Warm Period experienced to date, as well as the existence of the Little Ice Age of 1500–1850 AD, shown to have been the coldest period of the entire 3,000-year record.

Loehle cites 16 peer-reviewed scientific journal articles documenting the existence of the Medieval Warm Period in all parts of the world and 18 other articles documenting the worldwide occurrence of the Little Ice Age. In one of the more intriguing aspects of his study—of which Loehle makes no mention—both the Sargasso Sea and South African temperature records reveal the existence of a major temperature spike beginning in the early 1400s. This abrupt warming pushed temperatures considerably above the peak warmth of the twentieth century before falling back to pre-spike levels in the mid-1500s. Loehle's work thus provides support for the similar finding of higher-than-current temperatures at that time by McIntyre and McKittrick (2003) in their reanalysis of the data employed by Mann *et al.* to create their controversial “hockey stick” temperature history, which gives no indication of the occurrence of this high-temperature regime.

The models developed by Loehle also reveal the existence of three climate cycles previously identified by others. Loehle's seventh model, for example, identifies a 2,388-year cycle he describes as comparing “quite favorably to a cycle variously estimated as 2200, 2300, and 2500 years (Denton and Karlén, 1973; Karlén and Kuylenstierna, 1996; Magny, 1993; Mayewski *et al.*, 1997).” There is also a 490-year cycle that likely “corresponds to a 500-year cycle found previously (e.g. Li *et al.*, 1997; Magny, 1993; Mayewski *et al.*, 1997)” and a 228-year cycle that “approximates the 210-year cycle found by Damon and Jirikowic (1992).”

The compatibility of these findings with those of

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other studies that have identified solar forcing signals caused Loehle to conclude, “solar forcing (and/or other natural cycles) is plausibly responsible for some portion of 20th century warming.”

Other data sets also have provided evidence of a solar influence on temperature. Van Geel *et al.* (1999), for example, reviewed what was known at the time about the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. This analysis indicated “there is mounting evidence suggesting that the variation in solar activity is a cause for millennial scale climate change,” which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth’s orbit about the Sun. They also reviewed the evidence for mechanisms by which the solar-climate connection might be implemented, concluding “the climate system is far more sensitive to small variations in solar activity than generally believed” and “it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation.”

For the period 1856 to 2002, Scafetta and West (2003) compared the form of statistical fluctuations in the intermittency of solar flare activity with the form of statistical fluctuations in Earth’s near-surface air temperature as expressed as anomalies relative to the 1961–1990 mean. Both parameters studied were shown to possess time series properties characteristic of dynamical stochastic processes bearing imprints of a particular form of variability called a Levy-walk. The authors report “the affinity of the scaling exponents obtained through our analysis suggests that the Earth’s temperature anomalies inherit a Levy-walk memory component from the intermittency of solar flares,” which in turn suggests Earth’s near-surface air temperature fluctuations arise from variations in solar flare activity.

Scafetta and West found the best correspondence to solar flare variability was obtained for ocean, as opposed to land, temperatures. The oceans, due to their much greater compositional homogeneity and higher heat capacity, would be expected to mirror solar activity better than land masses do. It is also important to note the authors’ analysis dealt with short timescales, ranging from weeks to months. Over timescales of tens to hundreds of years, they note, correlations between solar activity and temperature have been well established. The shorter timescale

correlation they discovered implies a stronger physical connection between Earth’s climate and solar activity than most scientists had previously thought likely. This finding, in the words of Schewe *et al.* (2003), “suggests that for the large part, variations in global temperatures are beyond our control and are instead at the mercy of the Sun’s activity.”

The 16 authors of Mayewski *et al.* (2004) examined 50 globally distributed paleoclimate records in search of evidence for what they call rapid climate change (RCC) over the Holocene. This terminology is not to be confused with the rapid climate changes typical of glacial periods but is used in place of what the authors call the “more geographically or temporally restrictive terminology such as ‘Little Ice Age’ and ‘Medieval Warm Period.’” RCC events, as they also call them, are multi-century periods of time characterized by extremes of thermal and/or hydrological properties, rather than the much shorter periods of time during which the changes that led to these situations took place.

Mayewski *et al.* identify six RCCs during the Holocene: 9,000–8,000, 6,000–5,000, 4,200–3,800, 3,500–2,500, 1,200–1,000, and 600–150 cal yr BP, the last two of which intervals are the “globally distributed” Medieval Warm Period and Little Ice Age, respectively. With respect to these two periods, they write “the short-lived 1200–1000 cal yr BP RCC event coincided with the drought-related collapse of Maya civilization and was accompanied by a loss of several million lives (Hodell *et al.*, 2001; Gill, 2000), while the collapse of Greenland’s Norse colonies at ~600 cal yr BP (Buckland *et al.*, 1995) coincides with a period of polar cooling.”

The international team of scientists writes, “of all the potential climate forcing mechanisms, solar variability superimposed on long-term changes in insolation (Bond *et al.*, 2001; Denton and Karlén, 1973; Mayewski *et al.*, 1997; O’Brien *et al.*, 1995) seems to be the most likely important forcing mechanism.” They also note “negligible forcing roles are played by CH_4 and CO_2 ” and “changes in the concentrations of CO_2 and CH_4 appear to have been more the result than the cause of the RCCs.”

Raspopov *et al.* (2008), a team of eight researchers from China, Finland, Russia, and Switzerland, describe evidence making the case for a causative link, or set of links, between solar forcing and climate change.

Working with tree-ring width data obtained from two types of juniper found in Central Asia—

Juniperus turkestanica (related to variations in summer temperature in the Tien Shan Mountains) and *Sabina przewalskii* (related to variations in precipitation on the Qinghai-Tibetan Plateau)—Raspopov *et al.* employed band-pass filtering in the 180- to 230-year period range, wavelet transformation (Morlet basis) for the range of periods between 100 and 300 years, and spectral analysis in order to compare the variability in the two tree-ring records with independent $\Delta^{14}\text{C}$ variations representative of the approximate 210-year de Vries solar cycle over the past millennium. They found the approximate 200-year cyclical variations present in the palaeoclimatic reconstructions were well correlated ($R^2 = 0.58\text{--}0.94$) with similar variations in the $\Delta^{14}\text{C}$ data, suggesting the existence of a solar-climate connection. In addition, they say “the de Vries cycle has been found to occur not only during the last millennia but also in earlier epochs, up to hundreds of millions [of] years ago.”

After reviewing additional sets of published palaeoclimatic data from various parts of the world, the eight researchers concluded the same periodicity is evident in Europe, North and South America, Asia, Tasmania, Antarctica, and the Arctic, as well as “sediments in the seas and oceans,” citing 20 independent research papers in support of this statement. They conclude there is “a pronounced influence of solar activity on global climatic processes” related to “temperature, precipitation and atmospheric and oceanic circulation.”

Raspopov *et al.* also report there can sometimes be “an appreciable delay in the climate response to the solar signal,” as long as 150 years, and they note regional climate responses to the de Vries cycle “can markedly differ in phase,” even at distances of only hundreds of kilometers, because of “the nonlinear character of the atmosphere-ocean system response to solar forcing.” Nevertheless, their work testifies to the validity of their primary conclusion, that throughout the past millennium and stretching back in time as much as 250 million years, the de Vries cycle has been “one of the most intense solar activity periodicities that affected climatic processes.” As for the more recent historical significance of the de Vries cycle, Raspopov *et al.* write “the temporal synchrony between the Maunder, Sporer, and Wolf minima and the expansion of Alpine glaciers (Haeberlie and Holzhauser, 2003) further points to a climate response to the deep solar minima.”

Wanner *et al.* (2008)—18 climate scientists from 13 research institutions in Switzerland, Germany, the

United Kingdom, Belgium, and Russia—developed “a general framework for understanding climate changes during the last 6000 years.” They analyzed several hundred papers and concluded, among other things, “at decadal to multi-century timescales, climate variability shows a complex picture with indications of a possible role for (i) rapid changes of the natural forcing factors such as solar activity fluctuations and/or large tropical volcanic eruptions, (ii) internal variability including ENSO [El Niño Southern Oscillation] and NAO [North Atlantic Oscillation], (iii) changes of the thermohaline circulation, and (iv) complex feedback mechanisms between ocean, atmosphere, sea ice and vegetation.”

Wanner *et al.* also report “notable swings occurred between warm and cold periods, especially the hemispheric-scale warming leading into the Medieval Warm Period and subsequent cooling into the Little Ice Age,” the latter of which periods they say “appears at least to be a hemispheric phenomenon.” They also note model simulations support the inference that the Little Ice Age “may have been brought about by the coincidence of low Northern Hemisphere orbital forcing during the Late Holocene with unusually low solar activity and a high number of major volcanic events.”

de Jager and Duhau (2009) note “solar activity is regulated by the solar dynamo,” “the dynamo is a non-linear interplay between the equatorial and polar magnetic field components,” and “so far, in Sun-climate studies, only the equatorial component has been considered as a possible driver of tropospheric temperature variations.” Thus they set out to examine the neglected polar field’s possible influence on global temperature.

Based on “direct observations of proxy data for the two main solar magnetic field components since 1844,” de Jager and Duhau derived “an empirical relation between tropospheric temperature variation and those of the solar equatorial and polar activities.” When the two researchers applied this relationship to the period 1610–1995, they found a rising linear association for temperature vs. time, upon which were superimposed “some quasi-regular episodes of residual temperature increases and decreases, with semi-amplitudes up to $\sim 0.3^\circ\text{C}$,” and they note “the present period of global warming is one of them.”

de Jager and Duhau conclude, “the amplitude of the present period of global warming does not significantly differ from the other episodes of relative warming that occurred in earlier centuries.” The late twentieth century episode of relative warming is

merely “superimposed on a relatively higher level of solar activity than the others,” giving it the appearance of being unique when it isn’t.

Mazzarella (2008) analyzed historical series of solar wind turbulence, atmospheric circulation, the rotation of Earth (length of day, LOD), and sea surface temperature, finding an impressive correlation of $R=-0.97$ between the aa index and zonal pressure (ZI), when aa was shifted ahead five years. Between ZI and LOD the correlation was $R=-0.87$ with a lag of six years, while the correlation between LOD and SST was $R=-0.97$ with a lag of four years. Such relationships suggest an increase in solar wind speed causes a decrease in zonal atmospheric circulation after five years, which causes a deceleration of Earth’s rotation after four years, which ultimately causes a decrease in sea surface temperature after four years. A 60-year cycle in LOD was identified previously by Mazzarella (2007) at a confidence level greater than 99 percent. If the observed past correlation between LOD and SST continues in the future, the identified 60-year cycle hints toward a possible decline in SST starting in 2005. Recent data seem to support such a result.

Qian and Lu (2010) point out, “to understand the causes of 20th century global warming, the contributions of natural variability and human activities need to be determined,” adding “to make sound predictions for this century’s climate, understanding past climate change is important.” They began with the reconstructed global-mean temperature anomaly history of Mann *et al.* (2008), combined with HadCRUT3 data for 1000–2008, relative to 1961–1990 (Brohan *et al.*, 2006). After removing the mean temperatures of the Medieval Warm Period (MWP), Little Ice Age (LIA), and what they denoted the Global Warming Period (GWP), they used a wavelet transform procedure to identify four oscillations in the millennial temperature time series with periods of 21.1, 62.5, 116.0, and 194.6 years.

Next, they examined a reconstructed 400-year solar radiation series based on ^{10}Be data (Lean *et al.*, 1995; Bard and Frank, 2006), using the results they obtained “to analyze their causality relationship” with the periodic oscillations they had detected in the reconstructed millennial global-mean temperature series. The two Chinese researchers thus determined “the ~21-year, ~115-year and ~200-year periodic oscillations in global-mean temperature are forced by and lag behind solar radiation variability,” and the “relative warm spells in the 1940s and the beginning

of the 21st century resulted from overlapping of warm phases in the ~21-year and other oscillations.” They note “between 1994 and 2002 all four periodic oscillations reached their peaks and resulted in a uniquely warm decadal period during the last 1000 years,” representing the approximate temporal differential between the current Global Warming Period and the prior Medieval Warm Period.

It is important to note Qian and Lu did not need greenhouse gas emissions data to reconstruct the past thousand-year history of Earth’s global mean temperature; it was sufficient merely to employ known oscillations in solar radiation variability. The two authors write, “global-mean temperature will decline to a renewed cooling period in the 2030s, and then rise to a new high-temperature period in the 2060s.” Given the cessation in warming observed in the surface and lower tropospheric temperature records over the past decade, it appears their prediction is well on its way to being validated.

It is becoming increasingly clear that the millennial-scale oscillation of climate throughout the Holocene is the result of similar-scale oscillations in some aspect of solar activity. As Mayewski *et al.* (2004) suggested a decade ago, “significantly more research into the potential role of solar variability is warranted, involving new assessments of potential transmission mechanisms to induce climate change and potential enhancement of natural feedbacks that may amplify the relatively weak forcing related to fluctuations in solar output.”

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3.3.2 Northern Hemisphere

Evidence of the influence of the Sun on Northern Hemisphere temperatures can be found in the research of Bond *et al.* (2001), who examined ice-rafted debris

found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides (^{10}Be and ^{14}C) sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). This study is described in depth in Section 3.2 of this chapter.

Bond *et al.* found “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” and “a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic,” suggesting the cyclical climatic effects of the solar inferno are experienced throughout the world. Bond *et al.* also observed the oscillations in drift-ice they studied “persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system.”

Björck *et al.* (2001) assembled a wide range of lacustrine, tree-ring, ice-core, and marine records that reveal a Northern Hemispheric and possibly global cooling event of less than 200 years' duration with a 50-year cooling-peak centered at approximately 10,300 years BP. According to the authors, the onset of the cooling event broadly coincided with rising ^{10}Be fluxes, indicative of decreased solar or geomagnetic forcing; and because “no large magnetic field variation that could have caused this event has been found,” the authors postulate “the ^{10}Be maximum was caused by distinctly reduced solar forcing.” They also note the onset of the Younger Dryas is coeval with a rise in ^{10}Be flux, as is the Preboreal climatic oscillation.

Pang and Yau (2002) assembled and analyzed a vast amount of data pertaining to phenomena that have been linked reliably to variations in solar activity, including frequencies of sunspot and aurora sightings, the abundance of carbon-14 in the rings of long-lived trees, and the amount of beryllium-10 in the annual ice layers of polar ice cores. For their analysis of sunspot sightings, the authors used a catalogue of 235 Chinese, Korean, and Japanese records compiled by Yau (1988), a catalogue of 270 Chinese records compiled by Zhuang and Wang (1988), a time chart of 139 records developed by Clark and Stephenson (1979), and several later catalogues that made the overall record more complete.

Over the past 1,800 years, the authors identified “some nine cycles of solar brightness change,” including the well-known Oort, Wolf, Sporer, Maunder, and Dalton Minima. With respect to the

Maunder Minimum—which occurred between 1645 and 1715 and is widely acknowledged to have been responsible for some of the coldest weather of the Little Ice Age—they report the temperatures of that period “were about one-half of a degree Celsius lower than the mean for the 1970s, consistent with the decrease in the decadal average solar irradiance.” The Dalton Minimum occurred roughly between 1799 and 1820, with another dip in Northern Hemispheric temperatures. Since then, the authors state, “the Sun has gradually brightened” and “we are now in the Modern Maximum,” which is likely responsible for the warmth of the Current Warm Period.

Although the long-term variations in solar brightness Pang and Yau identified “account for less than 1% of the total irradiance, there is clear evidence that they affect the Earth’s climate.” The authors’ plot of total solar irradiance and Northern Hemispheric temperature from 1620 to the present (their Fig. 1c) indicates the former parameter (when appropriately scaled but without reference to any specific climate-change mechanism) can account for essentially all of the net change experienced by the latter parameter up to about 1980. After that time, the IPCC surface air temperature record rises dramatically, although radiosonde and satellite temperature histories largely match what would be predicted from the solar irradiance record. These facts could be interpreted as new evidence of the inaccuracy of the IPCC temperature history.

Rohling *et al.* (2003) “narrow down” temporal constraints on the millennial-scale variability of climate evident in ice-core $\delta^{18}\text{O}$ records by “determining statistically significant anomalies in the major ion series of the GISP2 ice core,” after which they conduct “a process-oriented synthesis of proxy records from the Northern Hemisphere.” With respect to the temporal relationships among various millennial-scale oscillations in Northern Hemispheric proxy climate records, the authors conclude a “compelling case” can be made for their being virtually in-phase, based on “the high degree of similarity in event sequences and structures over a very wide spatial domain,” and “the fact that our process-oriented synthesis highlights a consistent common theme of relative dominance shifts between winter-type and summer-type conditions, ranging all the way across the Northern Hemisphere from polar into monsoonal latitudes.” These findings, they additionally note, “corroborate the in-phase relationship between climate variabilities in the high northern latitudes and the tropics suggested in Blunier

et al. (1998) and Brook *et al.* (1999).”

Although individual cycles of the persistent climatic oscillation “appear to have different intensities and durations,” Rohling *et al.* further note, “a mean periodicity appears around ~1500 years (Mayewski *et al.*, 1997; Van Kreveld *et al.*, 2000; Alley *et al.*, 2001).” They further report “this cycle seems independent from the global glaciation state (Mayewski *et al.*, 1997; Bond *et al.*, 1999),” and “ ^{10}Be and delta ^{14}C records may imply a link with solar variability (Mayewski *et al.*, 1997; Bond *et al.*, 2001).”

Usoskin *et al.* (2003) point out “sunspots lie at the heart of solar active regions and trace the emergence of large-scale magnetic flux, which is responsible for the various phenomena of solar activity” that may influence Earth’s climate. They also state, “the sunspot number (SN) series represents the longest running direct record of solar activity, with reliable observations starting in 1610, soon after the invention of the telescope.” The authors compared SN data with the millennial-scale temperature reconstruction of Mann *et al.* (1999) by extending the directly measured SN record back in time to AD 850 using records of ^{10}Be cosmonuclide concentration derived from polar ice cores. In doing so, they employed detailed physical models “developed for each individual link in the chain connecting the SN with the cosmogenic isotopes,” and they combined these models in such a way that “the output of one model [became] the input for the next step.”

The resulting reconstructed SN history of the past millennium behaved very much like the infamous “hockey stick” temperature history of Mann *et al.* (1999). It slowly declined over the entire time period—with numerous modest oscillations associated with well-known solar maxima and minima—until the end of the Little Ice Age, whereupon it rose dramatically. Usoskin *et al.* report, for example, “while the average value of the reconstructed SN between 850 and 1900 is about 30, it reaches values of 60 since 1900 and 76 since 1944.” In addition, they report “the largest 100-year average of the reconstructed SN prior to 1900 is 44, which occurs in 1140–1240, i.e., during the medieval maximum,” but they note “even this is significantly less than the level reached in the last century.” Thus they conclude “the high level of solar activity since the 1940s is unique since the year 850.”

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3.3.3 North America

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,” after which they compared this history of glacial activity with “the ¹⁴C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability” and the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

The researchers found Alaska 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, Wiles *et al.* 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.* note “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 make no mention of possible CO₂-induced global warming in discussing their results; Alaskan glacial activity “has been shown to be primarily a record of summer temperature change (Barclay *et al.*, 1999)” and appears to be sufficiently well explained by solar and PDO variability alone. Four years later, Wiles *et al.* (2008) reconfirmed this solar-climate link in Alaska.

Regarding the nearby Columbia Icefield area of the Canadian Rockies, Luckman and Wilson (2005) used new tree-ring data to update a millennial temperature reconstruction for this region published in 1997. Their update employed different standardization techniques, such as the regional curve standardization method, in an effort to capture a greater degree of low frequency variability (centennial to millennial scale) than reported in the initial study. The new data set added more than one hundred years to the chronology and now covers the period AD 950–1994.

The updated proxy indicator of temperature showed considerable decadal- and centennial-scale variability, where generally warmer conditions prevailed during the eleventh and twelfth centuries, during approximately AD 1350–1450, and from about 1875 through the end of the record. 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 the other intervals).

According to Luckman and Wilson, the Columbia Icefield reconstruction “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,” which suggests the Sun is the main driver of these low frequency temperature trends.

Barron and Bukry (2007) extracted sediment cores from three sites on the eastern slope of the Gulf of California and, by examining these high-resolution records of diatoms and silicoflagellate assemblages, reconstructed sea surface temperatures there over the past 2,000 years. In all three of the sediment cores, the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures) was found to be greater during the Medieval Warm Period than at any other time over the 2,000-year period studied. During the Current Warm Period the

diatom’s relative abundance was lower than the 2,000-year mean, also in all three of the sediment cores. In addition, the first of the cores exhibited elevated *A. nodulifera* 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, Barron and Bukry determined “intervals of increased radiocarbon production (sunspot minima) correlate with intervals of enhanced biosilica productivity,” leading the two authors to conclude “solar forcing played a major role in determining surface water conditions in the Gulf of California during the past 2000 yr.” They note “reduced solar irradiance (sunspot minima) causes cooling of winter atmospheric temperatures above the southwest US” and “this strengthens the atmospheric low and leads to intensification of northwest winds blowing down the Gulf, resulting in increased overturn of surface waters, increased productivity, and cooler SST.”

Nederbragt and Thurow (2005) examined a high resolution marine sediment core taken from the Santa Barbara Basin (SBB) to determine whether millennial-scale climate cycles observed in the Atlantic Ocean were also present in the Pacific Ocean. Cross-spectral analyses revealed the presence of two dominant millennial-scale cycles in both the North Atlantic and Pacific SBB sedimentary records at frequencies of ~1000 and 2750 years. They also demonstrated these frequencies are similar to frequencies derived from a record of atmospheric Delta¹⁴C typically used as an indicator of solar activity. The coherence between the North Atlantic, Pacific SBB, and atmospheric Delta¹⁴C records strongly suggests, in the words of the authors, that “part of the climate variability during the Holocene is the result of variation in solar irradiance as an external forcing mechanism.”

Richey *et al.* (2007) constructed “a continuous decadal-scale resolution record of climate variability over the past 1400 years in the northern Gulf of Mexico” from a box core recovered in the Pigmy Basin, northern Gulf of Mexico [27°11.61’N, 91°24.54’W], based on “paired analyses of Mg/Ca and δ¹⁸O in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages.” They report “two multi-decadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm or warmer than near-modern conditions

between 1000 and 1400 yr B.P.,” while “foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was 2–2.5°C below modern SST.” 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,” providing additional evidence the historic warmth of Earth’s past was likely solar-induced.

Poore *et al.* (2003) developed a 14,000-year record of Holocene climate based primarily on the relative abundance of the planktic foraminifer *Globigerinoides sacculifer* found in two sediment cores. In reference to North Atlantic millennial-scale cool events 1–7 identified by Bond *et al.* (2001) as belonging to a pervasive climatic oscillation with a period of approximately 1,500 years, Poore *et al.* report distinct excursions to lower abundances of *G. sacculifer* “match within 200 years the ages of Bond events 1–6,” noting “major cooling events detected in the subpolar North Atlantic can be recognized in the GOM record.” They additionally note “the GOM record includes more cycles than can be explained by a quasiperiodic 1500-year cycle,” but such centennial-scale cycles with periods ranging from 200 to 500 years are also observed in the study of Bond *et al.* They note further their results “are in agreement with a number of studies indicating the presence of substantial century-scale variability in Holocene climate records from different areas,” specifically citing the reports of Campbell *et al.* (1998), Peterson *et al.* (1991), and Hodell *et al.* (2001). They also discuss evidence that leads them to conclude “some of the high-frequency variation (century scale) in *G. sacculifer* abundance in our GOM records is forced by solar variability.”

Lund and Curry (2004) analyzed a 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) covering the past 5,200 years. As they describe it, 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 report “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.”

A 2012 study found temperatures along the coast of Cape Hatteras pulsed according to the rhythm of the 1,000-year solar cycle (Cléroux *et al.*, 2012). The climate of British Columbia also has been driven by solar activity changes over the past 11,000 years (Gavin *et al.*, 2012).

Li *et al.* (2006) “recovered a 14,000-year mineral-magnetic record from White Lake (~41°N, 75°W), a hardwater lake containing organic-rich sediments in northwestern New Jersey, USA.” A comparison of the White Lake data with climate records from the North Atlantic sediments “shows that low lake levels at ~1.3, 3.0, 4.4, and 6.1 ka [1000 years before present] in White Lake occurred almost concurrently with the cold events at ~1.5, 3.0, 4.5, and 6.0 ka in the North Atlantic Ocean (Bond *et al.*, 2001)” and “these cold events are associated with the 1500-year warm/cold cycles in the North Atlantic during the Holocene” that have “been interpreted to result from solar forcing (Bond *et al.*, 2001).”

Long periods of warmth forced by variable solar activity in North America have occurred over and over again throughout the Holocene and beyond (Oppo *et al.*, 1998; Raymo *et al.*, 1998), suggesting the Current Warm Period also was instigated by this recurring phenomenon, not the CO₂ output of the Industrial Revolution.

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3.3.4 South America

Nordemann *et al.* (2005) examined tree rings from species sensitive to fluctuations in temperature and precipitation throughout the southern region of Brazil and Chile, along with sunspot data, via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding of the effects of solar activity, climate, and geophysical phenomena on the continent of South America, where the time interval covered by the tree-ring samples from Brazil was 200 years and that from Chile was 2,500 years. Results of the spectral analysis revealed periodicities in the tree rings that corresponded well with the DeVries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles, while wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Utilizing a lichenometric method for dating glacial moraines, the Bolivian and French research team of Rabatel *et al.* (2005) developed “the first detailed chronology of glacier fluctuations in a tropical area during the Little Ice Age,” focusing on fluctuations of the Charquini glaciers of the Cordillera Real in Bolivia, where they studied a set of 10 moraines that extend below the present glacier termini. The researchers determined the maximum glacier extension in Bolivia “occurred in the second half of the 17th century, as observed in many mountain areas of the Andes and the Northern Hemisphere.” In addition, they found “this expansion

has been of a comparable magnitude to that observed in the Northern Hemisphere, with the equilibrium line altitude depressed by 100–200 m during the glacier maximum.” They say “the synchronization of glacier expansion with the Maunder and Dalton minima supports the idea that solar activity could have cooled enough the tropical atmosphere to provoke this evolution.”

As for the magnitude and source of the cooling in the Bolivian Andes during the Little Ice Age, three years later Rabatal *et al.* (2008) estimated it to have been 1.1 to 1.2°C below that of the present, once again noting there was a “striking coincidence between the glacier expansion in this region of the tropics and the decrease in solar irradiance: the so-called ‘Maunder minimum’ (AD 1645-1715) during which irradiance might have decreased by around 0.24% (Lean and Rind, 1998) and could have resulted in an atmospheric cooling of 1°C worldwide (Rind *et al.*, 2004).”

Glasser *et al.* (2004) analyzed a large body of evidence related to glacier fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte (47°00’S, 73°39’W) and the Hielo Patagonico Sur (between 48°50’S and 51°30’S). The glacial advancements that occurred during the cold interval preceding the Roman Warm Period are “part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al.*, 1998; Wasson and Claussen, 2002), which coincides with an abrupt decrease in solar activity”; they add this observation “led van Geel *et al.* (2000) to suggest that variations in solar irradiance are more important as a driving force in variations in climate than previously believed.”

With respect to the most recent recession of Hielo Patagonico Norte outlet glaciers from their late historic moraine limits at the end of the nineteenth century, Glasser *et al.* say “a similar pattern can be observed in other parts of southern Chile (e.g., Kuylenstierna *et al.*, 1996; Koch and Kilian, 2001).” They note “in areas peripheral to the North Atlantic and in central Asia the available evidence shows that glaciers underwent significant recession at this time (cf. Grove, 1988; Savoskul, 1997),” which again suggests a globally distributed forcing factor such as cyclically variable solar activity.

Studying a bog, as opposed to a glacier, Chambers *et al.* (2007) presented new proxy climate data obtained from the Valle de Andorra northeast of Ushuaia, Tierra del Fuego, Argentina. These data, they emphasize, are “directly comparable” with

similar proxy climate data obtained in numerous studies conducted in European bogs, “as they were produced using identical laboratory methods.” Chambers *et al.* say their South American data show “a major climate perturbation at the same time as in northwest Europe,” which they describe as “an abrupt climate cooling” that occurred approximately 2,800 years ago. They write, “its timing, nature and apparent global synchronicity lend support to the notion of solar forcing of past climate change, amplified by oceanic circulation.”

Noting “rapid, high-magnitude climate changes might be produced within the Holocene by an inferred decline in solar activity (van Geel *et al.*, 1998, 2000, 2003; Bond *et al.*, 2001; Blaauw *et al.*, 2004; Renssen *et al.*, 2006),” the five European researchers conclude this “has implications for rapid, high-magnitude climate changes of the opposite direction—climatic warmings, possibly related to increases in solar activity.” They further note “for the past 100 years any solar influence would for the most part have been in the opposite direction (i.e., to help generate a global climate warming) to that inferred for c. 2800–2710 cal. BP.” They conclude this observation “has implications for interpreting the relative contribution of climate drivers of recent ‘global warming.’”

Polissar *et al.* (2006) worked with data derived from sediment records of two Venezuelan watersheds along with ancillary data obtained from other studies conducted in the same general region. They developed continuous decadal-scale histories of glacier activity and moisture balance in a part of the tropical Andes (the Cordillera de Merida) over the past millennium and a half, from which they deduced contemporary histories of regional temperature and precipitation.

The international (Canada, Spain, United States, Venezuela) team of scientists writes, “comparison of the Little Ice Age history of glacier activity with reconstructions of solar and volcanic forcing suggest that solar variability is the primary underlying cause of the glacier fluctuations,” because “the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ¹⁰Be and δ¹⁴C measurements”; “spectral analysis shows significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, closely matching the de Vries and Gleissberg oscillations identified from solar irradiance reconstructions”; and “solar and volcanic forcing are uncorrelated between AD 1520 and 1650, and the magnetic susceptibility record follows the solar-

irradiance reconstruction during this interval.” In addition, they note “four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima” and “temperature declines of $-3.2 \pm 1.4^{\circ}\text{C}$ and precipitation increases of $\sim 20\%$ are required to produce the observed glacial responses.”

Polissar *et al.* say their results “suggest considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability.”

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3.3.5 Asia

Bashkirtsev and Mashnich (2003), two scientists from

the Institute of Solar-Terrestrial Physics of the Siberian Division of the Russian Academy of Sciences, note in the Russian journal *Geomagnetizm i Aeronomiya*, “a number of publications report that the anthropogenic impact on the Earth’s climate is an obvious and proven fact,” when in their opinion “none of the investigations dealing with the anthropogenic impact on climate convincingly argues for such an impact.”

They cite the work of Friis-Christensen and Lassen (1991), who first noted the close relationship ($r = -0.95$) between the length of the sunspot cycle and the surface air temperature of the Northern Hemisphere over the period 1861–1989, where “warming and cooling corresponded to short (~10 yr) and prolonged (~11.5 yr) solar cycles, respectively.” They also cite the work of Zherebtsov and Kovalenko (2000), who established a high correlation ($r = 0.97$) between “the average power of the solar activity cycle and the surface air temperature in the Baikal region averaged over the solar cycle.” These two findings, Bashkirtsev and Mashnich contend, “leave little room for the anthropogenic impact on the Earth’s climate.” In addition, they note “solar variations naturally explain global cooling observed in 1950–1970, which cannot be understood from the standpoint of the greenhouse effect, since CO₂ was intensely released into the atmosphere in this period,” citing the work of Dergachev and Raspopov (2000).

Bashkirtsev and Mashnich conduct wavelet-spectra and correlation analyses of Irkutsk and world air temperatures and Wolf number data for the period 1882–2000, finding periodicities of 22 (Hale cycle) and 52 (Fritz cycle) years and reporting “the temperature response of the air lags behind the sunspot cycles by approximately 3 years in Irkutsk and by 2 years over the entire globe.”

Noting one could thus expect the upper envelope of sunspot cycles to reproduce the global temperature trend, they created such a plot and found “the lowest temperatures in the early 1900s correspond to the lowest solar activity (weak cycle 14), the further temperature rise follows the increase in solar activity; the decrease in solar activity in cycle 20 is accompanied by the temperature fall [from 1950–1970], and the subsequent growth of solar activity in cycles 21 and 22 entails the temperature rise [of the past quarter century].”

Bashkirtsev and Mashnich conclude “it has become clear that the current sunspot cycle (cycle 23) is weaker than the preceding cycles (21 and 22)” and “solar activity during the subsequent cycles (24 and

25) will be, as expected, even lower,” noting “according to Chistyakov (1996, 2000), the minimum of the secular cycle of solar activity will fall on cycle 25 (2021–2026), which will result in the minimum global temperature of the surface air (according to our prediction).”

Vaganov *et al.* (2000) utilized tree-ring width as a proxy for temperature to examine temperature variations in Asia over the past 600 years. According to a graph of the authors’ data, temperatures in the Asian subarctic exhibited a small positive trend from the start of the record until about 1750. Thereafter, a severe cooling trend ensued, followed by a 130-year warming trend from about 1820 through 1950, after which temperatures fell once again. The authors state the amplitude of twentieth century warming “does not go beyond the limits of reconstructed natural temperature fluctuations in the Holocene subarctic zone.” They also report finding a significant correlation with solar radiation and volcanic activity over the entire 600-year period ($R = 0.32$ for solar radiation, $R = -0.41$ for volcanic activity), and this correlation actually improved over the shorter interval of the industrial period, 1800 to 1990 ($R = 0.68$ for solar radiation, $R = -0.59$ for volcanic activity).

In this region of the world, where climate models predict large increases in temperature as a result of the historical rise in the air’s CO₂ concentration, real-world data show a cooling trend since around 1940, when the greenhouse effect of CO₂ should have been most prevalent. Where warming does exist in the record (between about 1820 and 1940), much of it correlates with changes in solar irradiance and volcanic activity—two factors free of anthropogenic influence.

In two additional paleoclimate studies from the continental interior of Russia’s Siberia, Kalugin *et al.* (2005) and Kalugin *et al.* (2007) analyzed sediment cores from Lake Teletskoye in the Altai Mountains (51°42.90’N, 87°39.50’E) to produce multi-proxy climate records spanning the past 800 years. Analyses of the multi-proxy records revealed several distinct climatic periods over the past eight centuries. The regional climate was relatively warm, with high terrestrial productivity, from AD 1210 to 1380. Thereafter, temperatures cooled, reaching peak deterioration between 1660 and 1700, which, in the words of Kalugin *et al.* (2005), “corresponds to the age range of the well-known Maunder Minimum (1645–1715)” of solar sunspot activity.

Aono and Kazui (2008) developed an uninterrupted 1,100-year history of March mean

temperature at Kyoto, Japan using phenological data on the times of full-flowering of cherry trees (*Prunus jamasakura*) acquired from old diaries and chronicles written at Kyoto. That record was reconciled with instrumental temperature measurements obtained over the period 1881–2005 and compared with the sunspot number history developed by Solanki *et al.* (2004).

The researchers report “the existence of four cold periods, 1330–1350, 1520–1550, 1670–1700, and 1825–1830, during which periods the estimated March mean temperature was 4–5°C, about 3–4°C lower than the present normal temperature,” and “these cold periods coincided with the less extreme periods [of solar activity], known as the Wolf, Spoerer, Maunder, and Dalton minima, in the long-term solar variation cycle, which has a periodicity of 150–250 years.” In addition, they report “a time lag of about 15 years was detected in the climatic temperature response to short-term solar variation.”

Kitagawa and Matsumoto (1995) analyzed $\delta^{13}\text{C}$ variations of Japanese cedars growing on Yakushima Island (30°20'N, 130°30'E) in an effort to reconstruct a high-resolution proxy temperature record over the past two thousand years. In addition, they applied spectral analysis to the $\delta^{13}\text{C}$ time series in an effort to learn if any significant periodicities were present in the record. They found significant decadal to centennial-scale variability throughout the record, with temperatures fluctuating by about 5°C across the series. Between AD 700–1200 they found a 1°C rise in average temperature (pre-1850 average), which the authors state “appears to be related to the ‘Medieval Warm Period.’” By contrast, temperatures were about 2°C below the long-term pre-1850 average during the multi-century Little Ice Age between AD 1580 and 1700. Kitagawa and Matsumoto also report finding significant temperature periodicities of 187, 89, 70, 55, and 44 years. Noting the 187-year cycle closely corresponds to the well-known Suess cycle of solar activity and the 89-year cycle compares well with the Gleissberg solar cycle, they conclude their findings provide further support for a Sun-climate relationship.

Ten years later, Cini Castagnoli *et al.* (2005) reexamined the Kitagawa and Matsumoto data set for evidence of recurring cycles using Singular Spectrum Analysis and Wavelet Transform, after which it was compared with a 300-year record of sunspots. Their analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity plus a second multi-decadal oscillation of about 87 years for the tree-ring series in phase with the amplitude modulation of the sunspot number series over the past

300 years. They concluded the overall phase agreement between the climate reconstruction and variation in the sunspot number series “favors the hypothesis that the [multi-decadal] oscillation” revealed in the record “is connected to the solar activity.”

Several studies have documented a solar influence on temperature in China from several proxy temperature indicators. Paulsen *et al.* (2003) utilized high-resolution records of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ from a stalagmite in Buddha Cave, central China [33°40'N, 109°05'E], to infer changes in climate over the past 1,270 years. 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.” The data also revealed a number of other cycles superimposed on these major millennial-scale temperature cycles, which they attributed to cyclical solar and lunar phenomena.

Tan *et al.* (2004) established an annual layer thickness chronology for a stalagmite from Beijing Shihua Cave and reconstructed a 2,650-year (BC 665–AD 1985) warm season (MJJA: May, June, July, August) temperature record for Beijing by calibrating the thickness chronology with the observed MJJA temperature record (Tan *et al.*, 2003). The warm season temperature record was “consistent with oscillations in total solar irradiance inferred from cosmogenic ^{10}Be and ^{14}C ” and “remarkably consistent with Northern Atlantic drift ice cycles that were identified to be controlled by the Sun through the entire Holocene [Bond *et al.*, 2001].” Both records clearly depict the start of the Current Warm Period, Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, Roman Warm Period, and the cold climate at the start of both records.

The authors conclude “the synchronism between the two independent Sun-linked climate records therefore suggests that the Sun may directly couple hemispherical climate changes on centennial to millennial scales.” The cyclical nature of the millennial-scale oscillation of climate evident in both climate records suggests there is no need to invoke rising atmospheric CO_2 concentrations as a cause of the Current Warm Period.

Working with a stalagmite found in Wanxiang Cave (33°19'N, 105°00'E), Zhang *et al.* (2008) developed a $\delta^{18}\text{O}$ record with an average resolution of 2.5 years covering the period AD 190 to 2003. According to the 17 authors, the $\delta^{18}\text{O}$ record “exhibits a series of centennial to multi-centennial fluctuations

broadly similar to those documented in Northern Hemisphere temperature reconstructions, including the Current Warm Period, Little Ice Age, Medieval Warm Period and Dark Age Cold Period.”

In addition, Zhang *et al.* state the $\delta^{18}\text{O}$ record “correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes.” In a commentary that accompanied Zhang *et al.*’s article, Kerr (2008) quotes other researchers calling the Zhang *et al.* record “amazing,” “fabulous,” and “phenomenal,” noting it “provides the strongest evidence yet for a link among Sun, climate, and culture.”

A team led by Professor ZhongHui Liu of Hong Kong University recently reported additional empirical evidence for solar forcing of temperatures around northern Tibetan Plateau, shown in Figure 3.3.5.1 below. The authors (He *et al.*, 2013), writing in *Chinese Science Bulletin*, presented the alkenone-based reconstruction of temperatures, at decadal resolution, from Lake Gahai and Lake Sugan covering about 2,600 and 2,200 years, respectively. The estimated warmth of the MWP period is as much as 1.9°C warmer than the modern warm period. The temperature reconstruction makes clear the close relationship of the warm-cold variations with the changing solar activity levels over the same interval.

Hong *et al.* (2000) developed a 6,000-year high-resolution $\delta^{18}\text{O}$ record from plant cellulose deposited in a peat bog in the Jilin Province of China (42° 20' N, 126° 22' E), from which they inferred the temperature history of that location over the past six millennia. They compared this record with a previously derived $\delta^{14}\text{C}$ tree-ring record representative of the intensity of solar activity over this period.

The area was found to have been relatively cold between 4000 and 2600 BC, then warming until it reached the maximum warmth of the record in about 1600 BC, after which it fluctuated about this warm mean for approximately 2,000 years. Starting about AD 350, the climate began to cool, with the most dramatic cold associated with three temperature minima centered at about AD 1550, 1650, and 1750, corresponding to the most severe cold of the Little Ice Age.

The authors call attention to their finding of “an obvious warm period represented by the high $\delta^{18}\text{O}$ from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe.” They also report “at that time, the northern boundary of the

cultivation of citrus tree (*Citrus reticulata* Blanco) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, and it has been estimated that the annual mean temperature was 0.9-1.0°C higher than at present.” Hong *et al.* also note “there is a remarkable, nearly one to one, correspondence between the changes of atmospheric $\delta^{14}\text{C}$ and the variation in $\delta^{18}\text{O}$ of the peat cellulose,” which led them to conclude the temperature history of the past 6,000 years at the site of their study has been “forced mainly by solar variability.”

Porter and Weijian (2006) analyzed 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers “represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation,” while “brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate.” They also report the climatic variations they discovered “correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water.”

The researchers state “the correspondence of these records over the full span of Holocene time implies a close relationship between North Atlantic climate and the monsoon climate of central China.” They also note the most recent of the episodic cold periods, which they identify as the Little Ice Age, began about AD 1370, while the preceding cold period ended somewhere in the vicinity of AD 810. Their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. Relating this millennial-scale climate cycle to the similar-scale drift-ice cycle of Bond *et al.* (2001) implies they accept solar forcing as the most likely cause of the alternating multi-century mild/moist and cold/dry periods of North-Central China.

Further evidence of a solar-climate link has been obtained from the Tibetan Plateau in China. Wang *et al.* (2002), for example, studied changes in $\delta^{18}\text{O}$ and NO_3^- in an ice core retrieved from the Guliya Ice Cap (35°17'N, 81°29'E), comparing their results with

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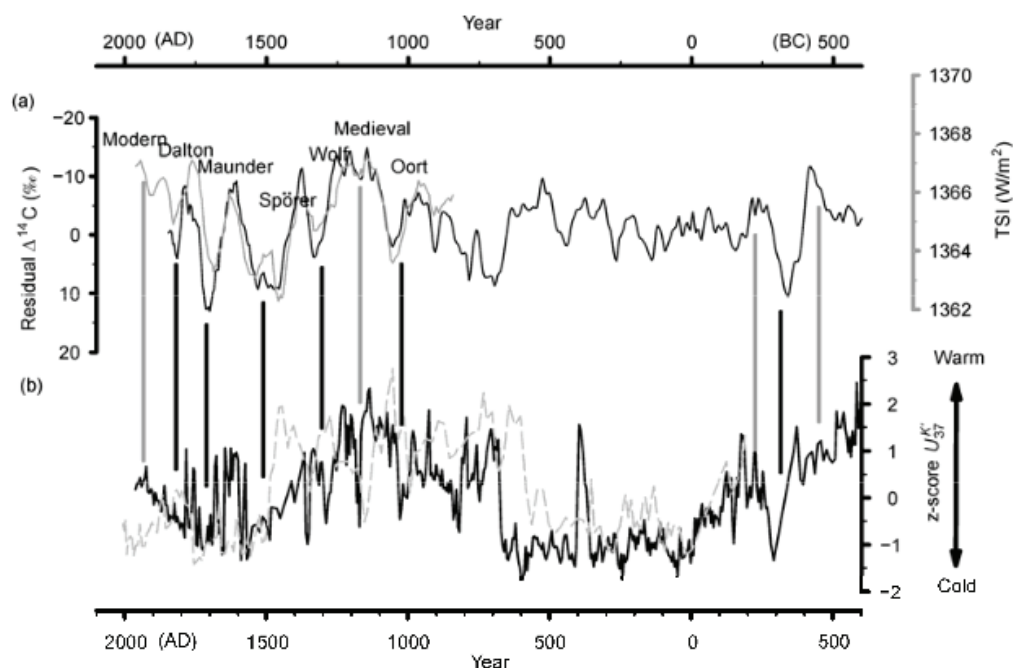


Figure 3.3.5.1. Correlations between solar activity proxies (top curves: TSI-grey; ^{14}C -black) and temperature proxies (bottom curves: Lake Suga-grey; Lake Gahai-black) from northern Tibetan Plateau. Reprinted with permission from He, Y.X., Liu, W.G., Zhao, C., Wang, Z., Wang, H.Y., Liu, Y., Qin, X.Y., Hu, Q.H., An, Z.S., and Liu, Z.H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

ancillary data from Greenland and Antarctica. Two cold events—a weak one around 9.6–9.2 thousand years ago (ka) and a strong one referred to as the “8.2 ka cold event”—were identified in the Guliya ice core record. The authors report these events occurred “nearly simultaneously with two ice-rafted episodes in the North Atlantic Ocean.” They also note both events occurred during periods of weakened solar activity.

Remarking that evidence for the 8.2 ka cold event “occurs in glacial and lacustrine deposits from different areas,” the authors say this evidence “suggests that the influence of this cold event may have been global.” They also say “comprehensive analyses indicate that the weakening of solar insolation might have been the external cause of the ‘8.2 ka cold event’” and “the cause of the cold event around 9.6–9.2 ka was also possibly related to the weaker solar activity.” The authors thus conclude these observations imply “millennial-scale climatic cyclicity might exist in the Tibetan Plateau as well as in the North Atlantic.”

Xu *et al.* (2002) studied plant cellulose $\delta^{18}\text{O}$ variations in cores retrieved from peat deposits west

of Hongyuan County at the northeastern edge of the Qinghai-Tibetan Plateau (32° 46'N, 102° 30'E). The authors report finding three consistently cold events centered at approximately 500, 700, and 900 AD, during what is sometimes referred to as the Dark Ages Cold Period. Then, for the period 1100–1300 AD, they report “the $\delta^{18}\text{O}$ of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the ‘Medieval Warm Period.’” Finally, they note “the periods 1370–1400 AD, 1550–1610 AD, [and] 1780–1880 AD recorded three cold events, corresponding to the ‘Little Ice Age.’”

Power spectrum analyses of their data revealed periodicities of 79, 88, and 123–127 years, “suggesting that the main driving force of Hongyuan climate change is from solar activities.” In a subsequent paper by the same authors, Xu *et al.* (2006) compared the Hongyuan temperature variations with solar activity inferred from atmospheric ^{14}C and ^{10}Be concentrations measured in a South Pole ice core, after which they performed cross-spectral analyses to determine the relationship between temperature and solar variability, comparing

their results with similar results obtained by other researchers.

Xu *et al.* (2006) report, “during the past 6000 years, temperature variations in China exhibit high synchrony among different regions, and importantly, are in-phase with those discovered in other regions in the northern hemisphere.” They also say their “comparisons between temperature variations and solar activities indicate that both temperature trends on centennial/millennial timescales and climatic events are related to solar variability.” The researchers conclude “quasi-100-year fluctuations of solar activity may be the primary driving force of temperature during the past 6000 years in China.”

Two years later Tan *et al.* (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau’s northeast margin since AD 960 based on an analysis of Chinese historical records, after which they compared the result with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories.

Tan *et al.* discovered “high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere.” Consequently, their precipitation record may be used to infer a Medieval Warm Period that stretched from approximately AD 960 to 1230, with temperature peaks in the vicinity of AD 1000 and 1215 that clearly exceeded the twentieth century peak temperature of the Current Warm Period. They also found “good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record.” These findings harmonize, in their words, with “numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene,” in support of which they attach 22 scientific references.

Tan *et al.* conclude the “synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity,” which apparently produced a Medieval Warm Period both longer and stronger than what has been experienced to date during the Current Warm Period in the northeast margin of the Tibetan Plateau.

Xu *et al.* (2008) studied decadal-scale temperature variations of the past six centuries derived from four high-resolution temperature indicators—the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of bulk carbonate, total carbonate content, and the detrended $\delta^{15}\text{N}$ of organic

matter—extracted from Lake Qinghai (36°32′–37°15′N, 99°36′–100°47′E) on the northeast Qinghai-Tibet plateau, comparing the resultant variations with proxy temperature indices derived from nearby tree rings and reconstructed solar activity. The analysis revealed “four obvious cold intervals during the past 600 years at Lake Qinghai, namely 1430–1470, 1650–1715, 1770–1820 and 1920–1940,” and “these obvious cold intervals are also synchronous with the minimums of the sunspot numbers during the past 600 years,” namely, “the Spörer, the Maunder, and the Dalton minimums.” These facts strongly suggest, in their words, “that solar activities may dominate temperature variations on decadal scales at the northeastern Qinghai-Tibet plateau.”

If the development of the significant cold of the Little Ice Age was driven by a change in some type of solar activity, it logically follows that the global warming of the twentieth century was driven primarily by the reversal of that trend in solar activity, not by the historical rise in the air’s CO_2 content. However, as also noted by Xu *et al.*, how small perturbations of solar activity have led “to the observed global warming, what is the mechanism behind it, etc., are still open questions.”

The authors write, “the middle reach of the Yangtze River possesses abundant depositional resources (e.g. stalagmite, peatland and lake sediments),” which “are reliable information carriers for paleoclimate and paleoenvironmental reconstruction.” They add “the reconstruction of long-term paleoclimate change would provide the premise for accurate prediction of the future.”

Soon *et al.* (2011) revealed a high degree of correlation between Chinese surface temperature records and two measures of solar radiation: a reconstruction of total solar irradiance (TSI) over the interval 1880–2002 (Figure 3.3.5.2) and a reconstruction of sunshine duration (Figure 3.3.5.3). The correlation between the data sets resembles an earlier correlation published by Soon (2005) between Arctic-wide surface temperature and TSI. Such strong correlations between temperature and solar-related indices from different geographical regions, together with the solar modulation of the Atlantic Meridional overturning circulation on multidecadal to centennial timescales (Soon, 2009), suggest solar forcing at the top of the atmosphere can and does persist to influence or drive climatic change near the surface of Earth. The simultaneous existence of the correlation between Chinese surface temperature with the two different measures of solar radiation may provide a

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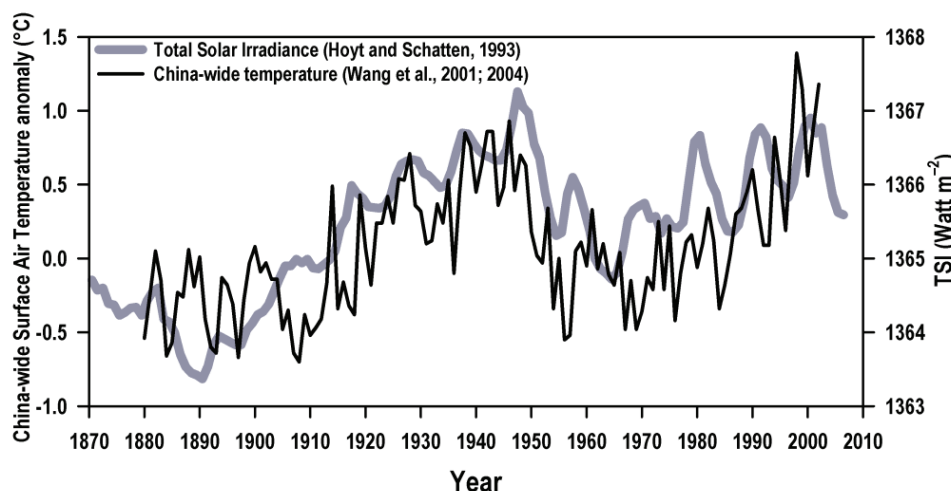


Figure 3.3.5.2. The empirical correlation between China-wide surface air temperature and estimated total solar irradiance from 1880 to 2002. Reprinted with permission from Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* 73: 2331–2344.

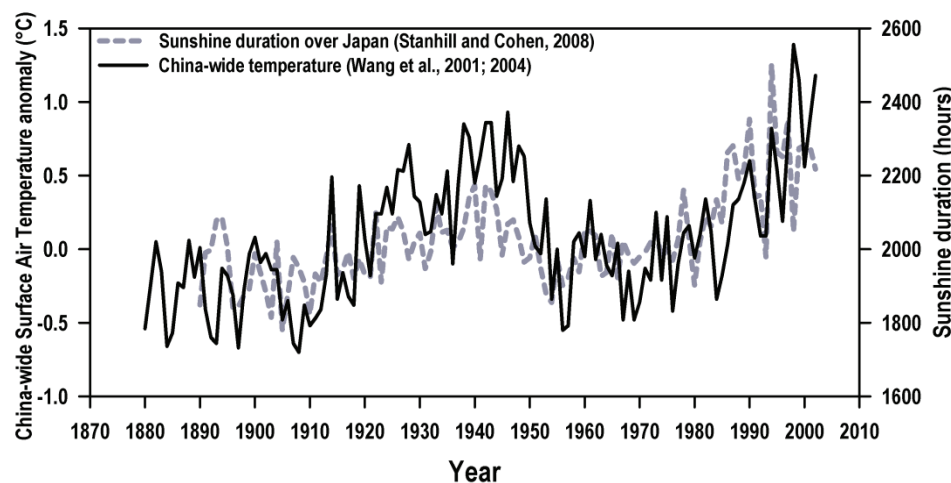


Figure 3.3.5.3. The empirical correlation between China-wide surface air temperature and the Japanese sunshine duration record from Stanhill and Cohen (2008) from 1890 to 2002. Also reprinted with permission from Soon *et al.* 2011.

strong physical constraint on how the Sun's irradiation can systematically modulate surface air temperature, at least in China.

Soon *et al.*'s work also explores the difficult challenge of having to explain how the transparency of the atmospheric column changes over time, through changing cloud fields and/or through more or less loading of particulate matters. According to the authors, the empirical results shown in their two figures reproduced here may be related to a key meteorological phenomenon involving the so-called Asian-African westerly jets, which Soon *et al.* (2011)

say provide direct evidence to support a real physical Sun-climate link, as opposed to a mere statistical coincidence. A specific wave-5 or -6 pattern of circumglobal teleconnection among five or six regional centers of action is used to explain why the widely separated meteorological regimes and climatic zones are interconnected.

It is important to point out the enormous difficulties of modeling such empirical observations even using the best computer climate models of our day. It is not an exaggeration to say this one hurdle—not knowing how solar radiation propagates and

changes from the top of the atmosphere to the near-surface or surface—has for at least the past 100 years prevented or slowed scientific progress into the Sun-climate connection.

Through phytolith analysis of a sediment core extracted at Zhoulao town in China's Jianli County in AD 2000, Gu *et al.* (2012) reconstructed a high-resolution record of paleoclimate change over the past 15,000 years in the middle reaches of the Yangtze River. They compared their results with paleoclimatic indicators derived from stalagmites, peatlands, North Atlantic deep-sea sediments (Bond *et al.*, 1997, 2001), the Loess Plateau of Central China, and Arabic Sea sediments. The five Chinese scientists identified eight climatic phases over the temperature reconstruction: the Last Glacial Maximum (20–14.8 cal ka BP), the Last Deglaciation (14.8–11.9 cal ka BP), a low temperature phase in the Early Holocene (11.9–8 cal ka BP), the Holocene Optimum (8–4.9 cal ka BP), the Holocene Katathermal (4.9–1.1 cal ka BP), the Medieval Warm Period (1.1–0.7 cal ka BP), the Little Ice Age (0.7–0.15 cal ka BP), and the Modern Warming (0.15 cal ka BP–present). In addition, they discovered the climate history of their research area had strong links with the contemporary histories of the Indian Summer Monsoon, the Asian Summer Monsoon, and the Holocene drift-ice events of the North Atlantic Ocean, which were discovered and described by Bond *et al.* (1997, 2001). Gu *et al.* conclude the correlation between their climate history and the Bond events “reveals that solar activity controls the Earth surface climate system at the centennial and millennial scales.”

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3.3.6 Europe

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, northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, starting with an in-depth analysis of the Great Aletsch glacier, the largest glacier in the European Alps.

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, during which the glacier grew in both mass and length, they find “during the Iron/Roman Age Optimum between c. 200 BC and AD 50,” better known as the Roman Warm Period, the glacier again retreated and “reached today’s extent or was even somewhat shorter than today.” Their records also identified the Dark Ages Cold Period, followed by “the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300,” a cold-wet phase “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. Holzhauser *et al.* also note written 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.”

Data pertaining to the Gorner glacier (the second largest in the Swiss Alps) and 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 Karlén, 1973; Magny, 1993; van Geel *et al.*, 1996; Bond *et al.*, 2001).” They conclude by stating “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.”

Hormes *et al.* (2006) determined radiocarbon dates of 71 samples of wood and peat found in the basal shear planes and proglacial outwashes of eight mid-latitude glaciers in the Central Swiss Alps. They found the dates clustered within discrete time intervals and were able to specify periods during which the glaciers’ leading edges were less extended than during the 1990s. “The glaciers investigated were less extensive than during the 1990s, with a shorter length during several defined periods,” they noted. These defined periods were: 10,110–9,550, 9,210–7,980, 7,450–6,500, 6,370–5,950, 5,860–3,360, 2,940–2,620 and 2,500–1,170 years before present. They also report “some of these periods with reduced glacier lengths are also documented on Svalbard in the Arctic, the Subantarctic Kerguelen islands in the Indian Ocean, and in Scandinavia.” They point out “the defined radiocarbon-dated periods with less extensive glaciers coincide well with periods of reduced ^{14}C production, pointing to the Sun’s role in glacier variation processes.”

Mauquoy *et al.* (2002a) extracted peat monoliths from ombrotrophic mires at Lille Vildmose, Denmark (56°50’N, 10°15’E) and Walton Moss, UK (54°59’N,

02°46’W), sites which, being separated by about 800 km, “offer the possibility of detecting supraregional changes in climate.” From these monoliths, vegetative macrofossils were extracted at contiguous 1-cm intervals and examined using light microscopy. Where increases in the abundances of *Sphagnum tenellum* and *Sphagnum cuspidatum* were found, a closely spaced series of ^{14}C AMS-dated samples immediately preceding and following each increase was used to “wiggle-match” date them (van Geel and Mook, 1989), enabling comparison of the climate-induced shifts with the history of ^{14}C production during the Holocene.

The work revealed a climatic deterioration that marked the beginning of a period of inferred cool, wet conditions that correspond fairly closely with the Wolf, Sporer, and Maunder Minima of solar activity, as manifest in contemporary $\delta^{14}\text{C}$ data. The authors report “these time intervals correspond to periods of peak cooling in 1000-year Northern Hemisphere climate records,” adding to the “increasing body of evidence” that “variations in solar activity may well have been an important factor driving Holocene climate change.”

Two years later, Mauquoy *et al.* (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes of climate change during the Holocene. The authors state “analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al.* (1995), van Geel *et al.* (1996), Speranza *et al.* (2000), Speranza (2000) and Mauquoy *et al.* (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977).” This close correspondence suggests “changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al.*, 1996, 1998, 1999, 2000) and the ‘Little Ice Age’ series of palaeoclimatic changes.”

Berstad *et al.* (2003) used a marine sediment core retrieved from the southern Norwegian continental margin to reconstruct sea surface temperatures (SSTs) from $\delta^{18}\text{O}$ data derived from the remains of the planktonic foraminifera species *Neogloboquadrina pachyderma* (summer temperatures) and *Globigerina bulloides* (spring temperatures). Among other things, the authors’ work depicts a clear connection between

the cold temperatures of the Little Ice Age and the reduced solar activity of the Maunder and Spörer solar minima, as well as between the warm temperatures of the most recent 70 years and the enhanced solar activity of the Modern solar maximum. The researchers clearly imply a causative connection between the SSTs and solar activity, as is also implied by the recent sunspot number reconstruction of Usoskin *et al.* (2003).

Sejrup *et al.* (2010) used two sediment cores extracted from the seabed of the eastern Norwegian Sea (~64°N, 3°E) to develop a 1,000-year proxy temperature record “based on measurements of $\delta^{18}\text{O}$ in *Neogloboquadrina pachyderma* (dextral form), a planktonic foraminifer that calcifies at relatively shallow depths within the Atlantic waters of the eastern Norwegian Sea during late summer,” which they compared with the temporal histories of various proxies of solar activity. The authors point out “the proxy record of solar variability from cosmogenic nuclides and telescopic observations of sunspots explains a substantial fraction of reconstructed Northern Hemisphere temperature variability during the pre-Industrial portion of the last millennium, with a simulated range of up to 0.4°C for plausible irradiance scaling and climate sensitivity,” citing Crowley (2000) and Ammann *et al.* (2007). They add, “at both the intra- and supra-decadal timescales there appear to be regional responses to solar forcing that are significantly larger than the global or hemisphere-scale response,” citing Shindell *et al.* (2001), Woods and Lean (2007), and Tung and Camp (2008).

Sejrup *et al.*’s analysis revealed “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.” In between these warm intervals were the colder temperatures of the Little Ice Age, when lower temperatures (thermal minima) occurred at the times of the Dalton, Maunder, Spörer and Wolf solar minima, such that the $\delta^{18}\text{O}$ proxy record of near-surface water temperature was found to be “robustly and near-synchronously correlated with various proxies of solar variability spanning the last millennium,” with decade- to century-scale temperature variability of 1 to 2°C revealing the Sun outshined nearly all other forcings of climate change in this region of Earth over the past millennium.

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, after which they identified and counted the approximately 2,000 annual varves in the cores and measured their individual thicknesses and mineral and organic matter contents. These climate-related data were compared with residual $\Delta^{14}\text{C}$ data derived from tree rings, which serve as a proxy for solar activity (Figure 3.3.6.1).

According to Haltia-Hovi *et al.*, 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

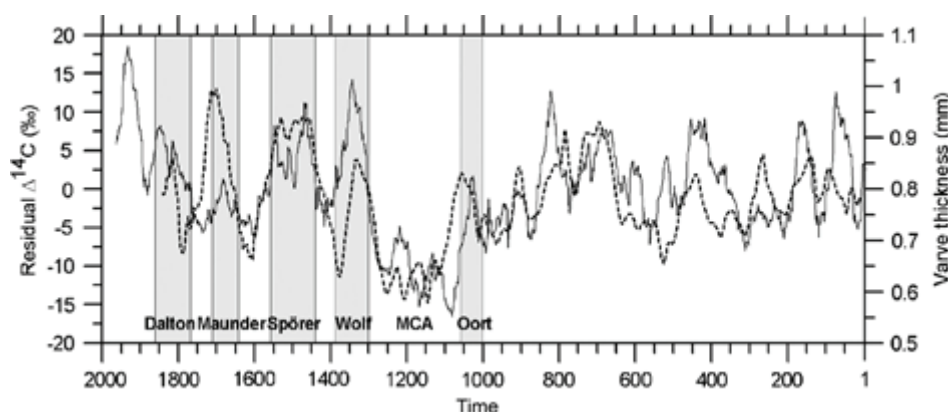


Figure 3.3.6.1. Residual $\Delta^{14}\text{C}$ data (dashed line) and varve thickness (smooth line) vs. time, specifically highlighting the Oort, Wolf, Spörer, Maunder and Dalton solar activity minima, as well as the “Medieval Climate Anomaly (also referred to as Medieval Warm Period),” during the contemporaneous “solar activity maxima in the Middle Ages.” Reprinted with permission 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.

Solar Forcing of Climate

solar forcing of the climate,” as depicted in the figure below for the case of varve thickness. In addition, the low deposition rate of mineral matter in Lake Lehmilampi 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 say 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 the lowest levels of both mineral and organic matter content, 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 that period was likely the warmest of the past two millennia in that part of the world.

Helama *et al.* (2010) examined the Sun-climate relationship in unprecedented detail over the mid- to late-Holocene, beginning a new exploration of Sun-climate co-variations on bimillennial and millennial timescales. They produced a well-dated and annually resolved tree-ring proxy temperature reconstruction from 5500 BCE to 2004 CE representative of the high Arctic region of Northern Lapland, Finland, and Norway (68–70°N, 20–30°E), after which they employed the reconstructed sunspot series for the past 11,000 years developed by Solanki and colleagues in 2004 as a proxy for their solar activity index. Although Helama *et al.* confirmed temperature oscillations on centennial and bicentennial timescales, they focused their study on bimillennial and millennial timescale variations.

Figure 3.3.6.2 shows the band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series are very well correlated if one introduces a time lag of about 70 years. The statistical correlations between the two Sun-climate variables change with time but become more significant during the past 2,000 years with $r = 0.796$ and $p = 0.0066$. The authors were unable to demonstrate similar positive or significant correlations for the Sun-climate variables for bimillennial (band-pass filtering of 1,150 to 3,000 years) scale variations for the past two thousand years (late Holocene), but stronger correlations (with $r = 0.877$ and $p = 0.0121$) were shown to exist between sunspot activity and temperatures at high-latitude Lapland for the Mid Holocene interval at the bimillennial timescale (not shown).

Helama *et al.* suggest the statistical correlations for the Sun and temperature series on millennial

timescales depicted in Figure 3.3.6.2 are probably realistic and physically meaningful, especially accounting for a time lag of 60 to 80 years. They posit solar activity may have driven the advection of cold surface waters southward and eastward in the subpolar North Atlantic, and that cold water perturbation may ultimately influence the production of the North Atlantic deep water down to a depth of 2,000 meters. Actions within the high Arctic would take time to propagate further south to affect the formation and working of the North Atlantic Meridional Overturning Circulation; such time lags, although in a shorter range of five to 30 years, have been shown by Eichler *et al.* (2010) and Soon (2009) to be necessary for a physical connection between changes in the Sun and climatic conditions around Europe and North and tropical Atlantic regions.

Helama *et al.* also briefly discuss plausible Sun-climate mechanisms through the atmosphere, invoking changing tropospheric-stratospheric temperature gradients. They ultimately conclude a pathway and mechanism involving the ocean for both memory and redistribution of heat are probably needed to explain what they observed.

Importantly for projections of future climate, Helama *et al.* point out “the near-centennial delay in climate in responding to sunspots indicates that the Sun’s influence on climate arising from the current episode of high sunspot numbers [which are the most pronounced of the entire record] may not yet have manifested itself fully in climate trends.” They note, “if neglected in climate models, this lag could cause an underestimation of twenty-first-century warming trends.”

Hanna *et al.* (2004) analyzed several climatic variables over the past century to determine whether there is “evidence of recent climatic changes” in Iceland. For the period 1923–2002, they found no trend in either annual or monthly sunshine data. Similar results were reported for annual and monthly pressure data, which exhibited semi-decadal oscillations throughout the 1820–2002 period but no significant upward or downward trend. Precipitation, by contrast, appears to have increased slightly, although the authors question the veracity of the trend, citing a number of biases that may have corrupted the database.

With respect to temperature, however, the authors report all stations at the locations they examined for this variable experienced a net warming since the mid-1800s. The warming was not linear over the entire period. Temperatures rose from their coldest

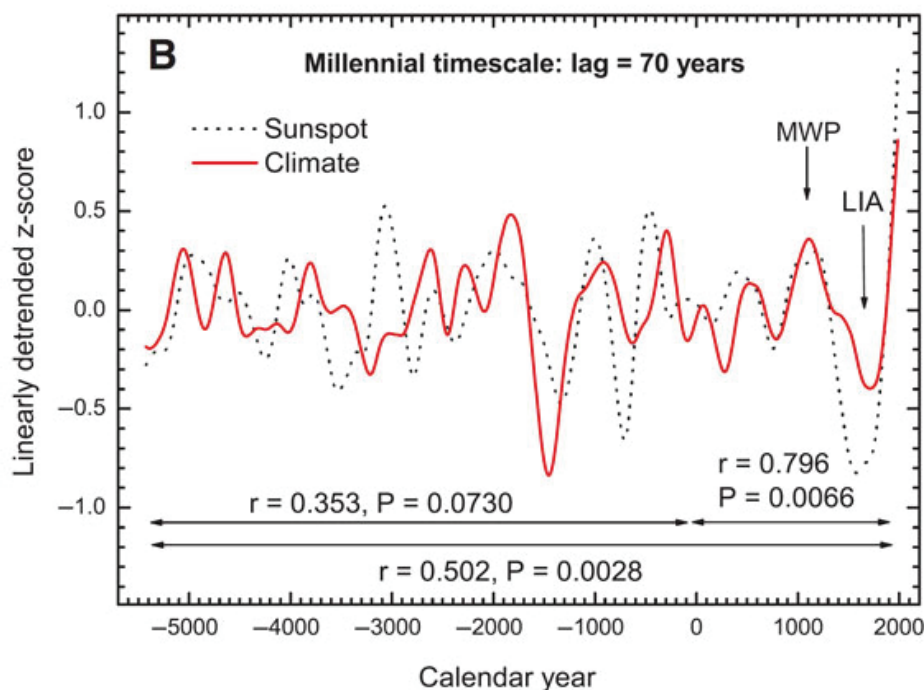


Figure 3.3.6.2. Band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series lagged by 70 years. Reprinted with permission from Helama, S., Fauria, M.M., Mielikainen, K., Timonen, M., and Eronen, M. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988..

levels in the mid-1800s to their warmest levels in the 1930s, whereupon they remained fairly constant for approximately three decades. Then came a period of rapid cooling, which ultimately gave way to the warming of the 1980s and 1990s. The warming of the past two decades has not resulted in temperatures rising above those observed in the 1930s; the authors state emphatically that “the 1990s was definitely not the warmest decade of the 20th century in Iceland, in contrast to the Northern Hemisphere land average.” A linear trend fit to the post-1930 data would indicate an overall temperature decrease since that time.

Hanna *et al.* find a significant correlation between 11-year running temperature means and sunspot numbers, plus the presence of a 12-year peak in their spectral analysis of the pressure data, which they say is “suggestive of solar activity.”

Other studies from northern Europe have found similar solar-climate linkages. Temperatures of a Swiss Alpine lake over the past 10,000 years were found to vary with changes in solar activity (Niemann *et al.*, 2012). Millennial-scale solar cycles also were found to be responsible for Alpine glacier movement

(Nussbaumer *et al.*, 2011). Similar cycles also were found in Finnish Lapland. Interestingly, each successive warm phase over the past 2,500 years has been colder than the previous (Esper *et al.*, 2012), marking a long-term cooling hardly compatible with the looming climate catastrophe alleged by the IPCC.

Norwegian studies have revealed a significant part of the warming there has been caused by the Sun (Solheim *et al.*, 2011; 2012; Humlum *et al.*, 2011; Vorren *et al.*, 2012). Climate and solar activity also are tightly coupled in Sweden (Kokfelt and Muscheler, 2012). In Finland, evidence of solar cycles has been discovered in tree rings (Ogurtsov *et al.*, 2011). Baltic Sea ice extent is known to be influenced by solar activity (Leal-Silva and Velasco Herrera, 2012), as is the ice on the Rhine River in Central Europe (Sirocko *et al.*, 2012). A massive cold period in Central Europe 2,800 years ago appears to have been triggered by a weak Sun (Martin-Puertas *et al.*, 2012). The North Atlantic deep water formation was found to be modulated by the Sun (Morley *et al.*, 2011). The famous rains in Northern Ireland are affected by changes in solar activity (Swindles *et al.*,

2012). Winds in Portugal blew particularly strong when the Sun was weak (Costas *et al.*, 2012). Solar activity fluctuations and the North Atlantic Oscillation (NAO) have contributed to Italy's climate of the past 10,000 years (Scholz *et al.*, 2012). A solar influence also could be detected in Italian salt marshes (Di Ritam 2013).

Noting “solar activity during the current sunspot minimum has fallen to levels unknown since the start of the 20th century” and “the Maunder minimum (about 1650–1700) was a prolonged episode of low solar activity which coincided with more severe winters in the United Kingdom and continental Europe,” Lockwood *et al.* (2010) were “motivated by recent relatively cold winters in the UK” to investigate the possible connection between these severe winters and low solar activity. They identified “regionally anomalous cold winters by detrending the Central England temperature record using reconstructions of the northern hemisphere mean temperature” and discovered “cold winter excursions from the hemispheric trend” do indeed “occur more commonly in the UK during low solar activity, consistent with the solar influence on the occurrence of persistent blocking events in the eastern Atlantic.” They state “colder UK winters (relative to the longer-term trend) can therefore be associated with lower open solar flux (and hence with lower solar irradiance and higher cosmic ray flux).”

Lockwood *et al.* are quick to note “this is a regional and seasonal effect relating to European winters and not a global effect.” But they also note “average solar activity has declined rapidly since 1985 and cosmogenic isotopes suggest an 8% chance of a return to Maunder minimum conditions within the next 50 years (Lockwood, 2010),” suggesting “despite hemispheric warming, the UK and Europe could experience more cold winters than during recent decades.”

Mangini *et al.* (2005) developed a highly resolved 2,000-year $\delta^{18}\text{O}$ proxy record of temperature obtained from a stalagmite recovered from Spannagel Cave in the Central Alps of Austria. They found the lowest temperatures of the past two millennia occurred during the Little Ice Age (AD 1400–1850), while the highest temperatures were found in the Medieval Warm Period (MWP: AD 800–1300). They report 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 different points during the MWP, their data indicate temperature spikes in excess

of 1°C above present (1995–1998) temperatures.

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, they say, these several data sets “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.”

Mangini *et al.* also 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 they note this correlation “suggests that solar variability was a major driver of climate in Central Europe during the past 2 millennia.” They 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 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.”

Two years later, Mangini *et al.* (2007) updated the 2005 study with additional data and compared it with the Hematite-Stained-Grain (HSG) history of ice-rafted debris in North Atlantic Ocean sediments developed by Bond *et al.* (2001). They found an undeniably good correspondence between the peaks and valleys of their $\delta^{18}\text{O}$ curve and the HSG curve. Recall from our previous discussion of Bond *et al.*'s work this conclusion: “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.”

Other researchers have found similar periodicities in their climate proxies. Turner *et al.* (2008), for example, found an ~1,500 year cycle in a climate history reconstructed from sediment cores extracted from two crater lake basins in central Turkey, which

they indicate “may be linked with large-scale climate forcing” such as that found in the North Atlantic by Bond *et al.* (1997, 2001). In addition, McDermott *et al.* (2001) found evidence of millennial-scale climate cycles in a $\delta^{18}\text{O}$ record from a stalagmite in southwestern Ireland, as did Sbaiffi *et al.* (2004) from two deep-sea sediment cores recovered from the Tyrrhenian Sea, which corresponded well with the North Atlantic solar-driven cycles of Bond *et al.* (1997).

In the Mediterranean Sea, Cini Castagnoli *et al.* (2002) searched for solar-induced variations in the $\delta^{13}\text{C}$ record of the foraminifera *Globigerinoides ruber* obtained from a sea core located in the Gallipoli terrace of the Gulf of Taranto (39°45'53"N, 17°53'33"E, depth of 178 m) over the past 1,400 years. Starting at the beginning of the 1,400-year record, the $\delta^{13}\text{C}$ values increased from about 0.4 per mil around 600 A.D. to a value of 0.8 per mil by 900 A.D. Thereafter, the $\delta^{13}\text{C}$ record remained relatively constant until about 1800, when it rose another 0.2 per mil to its present-day value of around 1.0 per mil.

Using statistical procedures, the authors identified three important cyclical components in their record, with periods of approximately 11.3, 100, and 200 years. Comparison of both the raw $\delta^{13}\text{C}$ and component data with the historical aurorae and sunspot time series, respectively, revealed the records are “associable in phase” and “disclose a statistically significant imprint of the solar activity in a climate record.” Three years later, Cini Castagnoli *et al.* (2005) extended the $\delta^{13}\text{C}$ temperature proxy from the Gulf of Taranto an additional 600 years, reporting an overall phase agreement between the climate reconstruction and variations in the sunspot number series that “favors the hypothesis that the [multi-decadal] oscillation revealed in $\delta^{13}\text{C}$ is connected to the solar activity.”

Chen *et al.* (2011) developed a high temporal resolution (four-year) sea surface temperature (SST) history based on a dinoflagellate cyst record obtained from a well-dated sediment core retrieved from a site in the Gulf of Taranto located at the distal end of the Po River discharge plume (39°50.07'N, 17°48.05'E). Their analysis revealed an era of “high stable temperatures between 60 BC and 90 AD followed by a decreasing trend between 90 AD and 200 AD.” And “consistent to earlier findings for the region,” they state “local air temperature during the Roman Period might have been warmer than that of the 20th century.” The authors write, “the observation of strong 11 years cyclicity in our records together with

a strong visual correlation of our temperature and river discharge records with the global variation in $\Delta^{14}\text{C}$ anomalies suggest that solar activity might have been an important climate forcing factor during this time.”

Desprat *et al.* (2003) conducted a high-resolution pollen analysis of a sediment core retrieved from the central axis of the Ria de Vigo in the south of Galicia (42°14.07'N, 8°47.37'W) to study the climatic variability of the last three millennia in northwest Iberia. According to the authors, 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, those periods were described by the authors as the “first cold phase of the Subatlantic period (975–250 BC),” “followed by the Roman Warm Period (250 BC–450 AD),” followed 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),” 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).” Based on this “millennial-scale climatic cyclicity over the last 3000 years,” which parallels “global climatic changes recorded in North Atlantic marine records (Bond *et al.*, 1997; Bianchi and McCave, 1999; Chapman and Shackleton, 2000),” Desprat *et al.* conclude “solar radiative budget and oceanic circulation seem to be the main mechanisms forcing this cyclicity in NW Iberia.”

Morellon *et al.* (2011) note, “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, providing “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 time period 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), which “clearly document warmer conditions from the twelfth to fourteenth centuries.” Morellon *et al.* conclude this warmth 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).”

Morellon *et al.* also note the occurrence of the LIA, which they recognize as occurring from AD 1300 to 1850. On the Iberian Peninsula, they report, “lower temperatures (Martinez-Cortizas *et al.*, 1999) characterize this period,” 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).” Following the LIA they identify the transition period of AD 1850–2004 that takes the region into the Current Warm Period.

In discussing these periods, the authors say “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 1460–1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1820).

Paleoclimatic studies from Europe provide more evidence for the global reality of solar-induced temperature oscillations pervading both glacial and interglacial periods, and these oscillations are looking more and more likely as the primary forcing agent responsible for driving temperature change during the Current Warm Period. The concurrent historical increase in the air’s CO₂ content, on the other hand, has likely exerted only minimal influence.

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3.3.7 Other Geographical Regions

Van Geel *et al.* (1999) examined the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. They write, “there is mounting evidence suggesting that the variation in solar activity is a cause for millennial-scale climate change,” which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth's orbit about the Sun. They add, “accepting the idea of solar forcing of Holocene and Glacial climatic shifts has major implications for our view of present and future climate,” for it implies, as they note, “the climate system is far more sensitive to small variations in solar activity than generally believed” and “it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation.”

Tyson *et al.* (2000) obtained a quasi-decadal-resolution record of oxygen and carbon-stable isotope data from a well-dated stalagmite recovered from Cold Air Cave in the Makapansgat Valley, 30 km southwest of Pietersburg, South Africa. They augmented that record with temperature data reconstructed from color variations in banded growth-layer laminations of the stalagmite derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981–1995, which had a correlation of +0.78 that was significant at the 99 percent confidence level.

The authors found both the Little Ice Age (prevailing from about AD 1300 to 1800) and the Medieval Warm Period (prevailing from before AD 1000 to around 1300) to be distinctive features of the

climate of the last millennium. Compared with the period 1961–1990, the Little Ice Age, “a widespread event in South Africa specifically and southern Africa generally,” was characterized by a mean annual temperature depression of about 1°C at its coolest point. The Medieval Warm Period, by contrast, was as much as 3–4°C warmer at its warmest point. The researchers also note the coolest point of the Little Ice Age corresponded with the Maunder Minimum of sunspot activity and the Medieval Warm Period corresponded with the Medieval Maximum in solar activity.

In a study demonstrating a solar-climate link on shorter decadal to centennial time scales, Domack *et al.* (2001) examined ocean sediment cores obtained from the Palmer Deep on the inner continental shelf of the western Antarctic Peninsula (64° 51.71' S, 64° 12.47' W) to produce a high-resolution proxy temperature history of that area spanning the past 13,000 years. They identified five prominent palaeo-environmental intervals over the past 14,000 years: (1) a “Neoglacial” cool period beginning 3,360 years ago and continuing to the present, (2) a mid-Holocene climatic optimum from 9,070 to 3,360 years ago, (3) a cool period beginning 11,460 years ago and ending at 9,070 years ago, (4) a warm period from 13,180 to 11,460 years ago, and (5) cold glacial conditions prior to 13,180 years ago. Spectral analyses of the data revealed decadal and centennial-scale temperature cycles superimposed upon these broad climatic intervals. Throughout the current Neoglacial period, they report finding “very significant” (above the 99 percent confidence level) peaks, or oscillations, that occurred at intervals of 400, 190, 122, 85, and 70 years, which they suggest are perhaps driven by solar variability.

Dima *et al.* (2005) performed Singular Spectrum Analysis on a Rarotonga coral-based sea surface temperature (SST) reconstruction from the warmer ocean waters off the Cook Islands, South Pacific Ocean in an effort to determine the dominant periods of multidecadal variability in the series over the period 1727–1996. Their work revealed two dominant multidecadal cycles with periods of about 25 and 80 years. These modes of variability were determined to be similar to multidecadal modes found 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 well-known 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.

Bard and Frank (2006) reviewed what is known and unknown about solar variability and its effects on Earth’s climate over the past few decades, the past few centuries, the entire Holocene, and orbital timescales. With respect to the three suborbital time scales, Bard and Frank conclude, “it appears that solar fluctuations were involved in causing widespread but limited climatic changes, such as the Little Ice Age (AD 1500–1800) that followed the Medieval Warm Period (AD 900–1400).” They write, “the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: The so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500–1800).”

Bard and Frank note, “Bond *et al.* (1997, 2001) followed by Hu *et al.* (2003) proposed that variations of solar activity are responsible for quasi-periodic climatic and oceanographic fluctuations that follow cycles of about one to two millennia.” They write, “the succession from the Medieval Warm Period to the Little Ice Age would thus represent the last [such] cycle,” leading them to conclude “our present climate is in an ascending phase on its way to attaining a new warm optimum” resulting from some form of solar variability. In addition, they note, “a recent modeling study suggests that an apparent 1500-year cycle could arise from the superimposed influence of the 90 and 210 year solar cycles on the climate system, which is characterized by both nonlinear dynamics and long time scale memory effects (Braun *et al.* 2005).”

The studies discussed in this and previous subsections examining solar influence on temperature demonstrate the warming of Earth since the termination of the Little Ice Age is not unusual or different from other climate changes of the past millennium, when atmospheric CO₂ concentrations were stable, lower than at present, and not responsible for the observed variations in temperature. This further suggests the warming of the past century had little to do with the contemporaneous historical increase in the air’s CO₂ content.

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3.4 Precipitation

Many researchers have examined historical proxy temperature changes over the past millennia and beyond in an attempt to quantify the magnitude, frequency, and causes of natural climate variability. However, temperature is not always the best measure

of climate, and it is certainly not the only measure. Some studies, for example, have examined the millennial range and rate of change of hydrologic and atmospheric circulation; changes in these parameters are important because they are involved in more than half of Earth's poleward transfer of heat (Peixoto and Oort, 1992).

In one such study, Maasch *et al.* (2005) examined changes in eight well-dated high-resolution climate-related records over the past two millennia: K^+ concentrations from the GISP2 ice core in Greenland, Na^+ concentrations from the Siple Dome ice core in Antarctica, percent Ti from an ocean sediment core in the Cariaco basin, Fe intensity from a marine core near the coast of mid-latitude Chile, oxygen isotope fractions from Punta Laguna near the Yucatan, carbon isotope data from a speleothem in Makapansgat, South Africa, percent of shallow water diatoms from Lake Victoria, and lake levels from Lake Naivasha in equatorial Africa. The eight data sets were compared with a history of atmospheric $\Delta^{14}C$, a proxy for solar variability obtained from tree rings, to ascertain what, if any, solar influence operated on these parameters.

Comparison of the $\Delta^{14}C$ solar proxy data with the eight climate-related data sets revealed over the past 2,000 years there has been a “strong association between solar variability and globally distributed climate change.” This “remarkable coherence” among the data sets was particularly noticeable in the Medieval Warm Period to Little Ice Age transition, as well as throughout the Little Ice Age.

In this section we review studies that show past trends in precipitation are likely explained better by solar variability than by the IPCC's preferred explanation, rising atmospheric CO_2 concentrations.

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3.4.1 North America

Kristjansson *et al.* (2002) examined the relationship between the Sun and low-level clouds, which are correlated with precipitation. They note solar irradiance “varies by about 0.1% over the 11-year solar cycle, which would appear to be too small to

have an impact on climate.” Nevertheless, they report “persistent claims have been made of 11-year signals in various meteorological time series, e.g., sea surface temperature (White *et al.*, 1997) and cloudiness over North America (Udelhofen and Cess, 2001).”

Kristjansson *et al.* “re-evaluate[d] the statistical relationship between low cloud cover and solar activity adding 6 years of ISCCP [International Satellite Cloud Climatology Project] data that were recently released.” For the period 1983–1999, they compared temporal trends of solar irradiance at the top of the atmosphere with low cloud cover trends derived from satellite-borne instruments that provided two measures of cloud cover: full temporal coverage and daytime-only coverage. They found “solar irradiance correlates well with low cloud cover,” with the significance level of the correlation being 98 percent for full temporal coverage and 90 percent for daytime-only coverage. In addition, as would be expected if the variations in cloud cover were driven by variations in solar irradiance, they also report lagged correlations between the two parameters revealed a maximum correlation between solar irradiance and low cloud cover when the former leads the latter by one month for full temporal coverage and by four months for daytime-only coverage.

Kristjansson *et al.* observed “low clouds appear to be significantly inversely correlated with solar irradiance,” leading them to suggest a possible physical mechanism that could explain this phenomenon. This mechanism “acts through UV [ultraviolet radiation] in the stratosphere affecting tropospheric planetary waves and therefore the subtropical highs, modulated by an interaction between sea surface temperature [SST] and lower tropospheric static stability,” which “relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics.” Based on experimentally determined values of factors that enter into this scenario, they obtained a value for the amplitude of the variation in low cloud cover over a solar cycle that “is very close to the observed amplitude.”

Other authors have examined lake level fluctuations, which are generally highly dependent on precipitation levels. Cumming *et al.* (2002), for example, studied a sediment core retrieved from Big Lake (51°40'N, 121°27'W) on the Cariboo Plateau of British Columbia, Canada, carefully dating it and deriving estimates of changes in precipitation-sensitive limnological variables (salinity and lake depth) from transfer functions based on modern

distributions of diatom assemblages in 219 lakes from western Canada.

On the basis of observed changes in patterns of the floristic composition of diatoms over the past 5,500 years, Cumming *et al.* report “alternating millennial-scale periods of high and low moisture availability were inferred, with abrupt transitions in diatom communities occurring 4960, 3770, 2300 and 1140 cal. yrs. BP.” They also find “periods of inferred lower lake depth correspond closely to the timing of worldwide Holocene glacier expansions” and the mean length of “the relatively stable intervals between the abrupt transitions ... is similar to the mean Holocene pacing of IRD [ice rafted debris] events ... in the North Atlantic,” described by Bond *et al.* (1997) and attributed to “solar variability amplified through oceanic and atmospheric dynamics,” as detailed by Bond *et al.* (2001).

Li *et al.* (2006, 2007) also developed a precipitation proxy from a lake-level record, based on lithologic and mineral magnetic data from the Holocene sediments of White Lake, New Jersey, northeastern USA (41°N, 74.8°W), the characteristics of which they compared with a host of other paleoclimatic reconstructions from this region and beyond.

According to the authors of these two papers (Li *et al.*, 2006; 2007), the lake-level history revealed low lake levels at ~1.3, 3.0, 4.4, and 6.1 thousand years before present. Comparison of the results with drift-ice records from the North Atlantic Ocean according to Li *et al.* (2007) “indicates a striking correspondence,” as they “correlate well with cold events 1, 2, 3 and 4 of Bond *et al.* (2001).” They also report a comparison of their results with those of other land-based studies suggests “a temporally coherent pattern of climate variations at a quasi-1500-year periodicity at least in the Mid-Atlantic region, if not the entire northeastern USA.” In addition, they note “the Mid-Atlantic region was dominated by wet conditions, while most parts of the conterminous USA experienced droughts, when the North Atlantic Ocean was warm.”

The three researchers say the dry-cold correlation they found “resembles the modern observed relationship between moisture conditions in eastern North America and the North Atlantic Oscillation (NAO), but operates at millennial timescales, possibly through modulation of atmospheric dynamics by solar forcing.” In this regard they write the Sun-climate link on millennial timescales has “been demonstrated in several records (e.g., Bond *et al.*, 2001; Hu *et al.*,

2003; Niggemann *et al.*, 2003), supporting solar forcing as a plausible mechanism for modulating the AO [Arctic Oscillation]/NAO at millennial timescales.”

Dean *et al.* (2002) analyzed the varve thickness and continuous gray-scale density of sediment cores taken from Elk Lake, Minnesota (47°12'N, 95°15'W) for the past 1,500 years. They identified significant periodicities throughout the record, including multidecadal periodicities of approximately 10, 29, 32, 42, and 96 years, and a strong multicentennial periodicity of about 400 years, leading them to wonder whether the observed periodicities are manifestations of solar-induced climate signals, for which they present strong correlative evidence. The 10-year oscillation was found to be strongest in the time series between the fourteenth and nineteenth centuries, during the Little Ice Age, and may have been driven by the 11-year sunspot cycle.

Lozano-Garcia *et al.* (2007) conducted a high-resolution multi-proxy analysis of pollen, charcoal particles, and diatoms found in the sediments of Lago Verde (18°36'46" N, 95°20'52"W)—a small closed-basin lake on the outskirts of the Sierra de Los Tuxtlas (a volcanic field on the coast of the Gulf of Mexico)—which covered the past 2,000 years. The five Mexican researchers say their data “provide evidence that the densest tropical forest cover and the deepest lake of the last two millennia were coeval with the Little Ice Age, with two deep lake phases that follow the Sporer and Maunder minima in solar activity.” In addition, they suggest “the high tropical pollen accumulation rates limit the Little Ice Age’s winter cooling to a maximum of 2°C,” and they conclude the “tropical vegetation expansion during the Little Ice Age is best explained by a reduction in the extent of the dry season as a consequence of increased meridional flow leading to higher winter precipitation.” Lozano-Garcia *et al.* conclude, “the data from Lago Verde strongly suggest that during the Little Ice Age lake levels and vegetation at Los Tuxtlas were responding to solar forcing and provide further evidence that solar activity is an important element controlling decadal to centennial scale climatic variability in the tropics (Polissar *et al.*, 2006) and in general over the North Atlantic region (Bond *et al.*, 2001; Dahl-Jensen *et al.*, 1998).”

Hughes *et al.* (2006) derived a multi-proxy palaeoclimate record from Nordan’s Pond Bog, a coastal plateau bog in Newfoundland, based on “analyses of plant macrofossils, testate amoebae and the degree of peat humification,” enabling them to

create “a single composite reconstruction of bog surface wetness (BSW)” they compare with “records of cosmogenic isotope flux.”

“At least 14 distinctive phases of increased BSW may be inferred from the Nordan’s Pond Bog record,” they write, commencing at 8,270 cal. years BP, and “comparisons of the BSW reconstruction with records of cosmogenic isotope flux ... suggest a persistent link between reduced solar irradiance and increased BSW during the Holocene.” Hughes *et al.* further conclude the “strong correlation between increased ^{14}C production [which accompanies reduced solar activity] and phases of maximum BSW supports the role of solar forcing as a persistent driver of changes to the atmospheric moisture balance throughout the Holocene.” Consequently, the authors state, “evidence suggesting a link between solar irradiance and sub-Milankovitch-scale palaeoclimatic change has mounted” and the “solar hypothesis, as an explanation for Holocene climate change, is now gaining wider acceptance.”

Asmerom *et al.* (2007) developed a high-resolution Holocene climate proxy for the southwest United States from $\delta^{18}\text{O}$ variations in a stalagmite obtained in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw $\delta^{18}\text{O}$ data revealed significant peaks the researchers say “closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993).” Their cross-spectral analysis of the $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ data confirmed the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. They suggest the proposed solar link to Holocene climate operates “through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean.”

Schmidt *et al.* (2012) found Florida was drier when the Sun was weak and wetter when the Sun was strong. And Nichols *et al.* (2012) note the rains in Maine over the past 7,000 years have been controlled by the sun.

Since the warming of the twentieth century appears to represent the most recent rising phase of

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the Bond cycle, which in its previous rising phase produced the Medieval Warm Period (see Bond *et al.*, 2001), and since we could still be embedded in that rising temperature phase, it is reasonable to expect the desert southwest of the United States could experience more intense aridity while wetter conditions prevail in the monsoon regions of Asia, without greenhouse gases playing any role.

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3.4.2 South America

Nordemann *et al.* (2005) analyzed tree rings from species sensitive to fluctuations in precipitation from the southern region of Brazil and Chile along with sunspot data via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding

of the effects of solar activity, climate, and geophysical phenomena on the continent of South America. The tree-ring samples from Brazil covered 200 years and those from Chile covered 2,500 years. The spectral analysis revealed periodicities in the tree rings that corresponded well with the de Vries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles; wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Baker *et al.* (2005) used a sediment core retrieved from the main basin of Lake Titicaca (16°S, 69°W) on the Altiplano of Bolivia and Peru to reconstruct the lake-level history of that South American water body over the past 13,000 years at decadal to multidecadal resolution based on $\delta^{13}\text{C}$ measurements of sediment bulk organic matter. The authors report “the pattern and timing of lake-level change in Lake Titicaca is similar to the ice-rafted debris record of Holocene Bond events, demonstrating a possible coupling between precipitation variation on the Altiplano and North Atlantic sea-surface temperatures.” Noting “cold periods of the Holocene Bond events correspond with periods of increased precipitation on the Altiplano,” they further conclude “Holocene precipitation variability on the Altiplano is anti-phased with respect to precipitation in the Northern Hemisphere monsoon region.” They add, “the relationship between lake-level variation at Lake Titicaca and Holocene Bond events also is supported by the more coarsely resolved (but very well documented) record of water-level fluctuations over the past 4000 years based on the sedimentology of cores from the shallow basin of the lake (Abbott *et al.*, 1997).”

Haug *et al.* (2001) utilized the titanium and iron concentrations of an ocean sediment core taken from a depth of 893 meters in the Cariaco Basin on the Northern Shelf of Venezuela (10°42.73'N, 65°10.18'W) to infer variations in the hydrologic cycle over northern South America over the past 14,000 years. They found titanium and iron concentrations 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 Holocene Optimum (10.5 to 5.4 thousand years ago), concentrations of these metals remained at or near their highest values, suggesting wet conditions and an enhanced hydrologic cycle for more than five thousand years. The largest century-scale variations in

precipitation are inferred in the record between approximately 3.8 and 2.8 thousand years ago, as the amounts of these metals in the sediment record varied widely over short time intervals. Higher precipitation 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).

The authors say the regional changes in precipitation “are best explained by shifts in the mean latitude of the Atlantic Intertropical Convergence Zone,” which, in turn, “can be explained by the Holocene history of insolation, both directly and through its effect on tropical Pacific sea surface conditions.”

In South America the Sun has controlled the distribution and intensity of the monsoon rains (Vuille *et al.*, 2012), a solar influence on precipitation also has been found for Brazil (Gusec and Martin, 2012; Rampelotto *et al.*, 2012), and solar cycles have been detected in the water masses of the deep sea (Seidenglanz *et al.*, 2012). The field of research in solar-climate interaction is more active than ever (de Wit *et al.*, 2010; Stauning, 2011; Raspopov *et al.*, 2011; Kern *et al.*, 2012).

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3.4.3 Africa

Neff *et al.* (2001) investigated the relationship between a ^{14}C tree-ring record and a $\delta^{18}\text{O}$ proxy record of monsoon rainfall intensity as recorded in calcite $\delta^{18}\text{O}$ data obtained from a stalagmite in northern Oman. The correlation between the two data sets, covering the period 9,600–6,100 years before present, was reported to be “extremely strong.” 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 tree-ring records are generally attributed to variations in solar activity and

intensity, and because of this particular ^{14}C record’s strong correlation with the $\delta^{18}\text{O}$ record and the closely corresponding results of the spectral analyses, Neff *et al.* conclude there is “solid evidence” that both signals (the ^{14}C and $\delta^{18}\text{O}$ records) are responding to solar forcing.

Stager *et al.* (2003) studied changes in diatom assemblages preserved in a sediment core extracted from Pilkington Bay, Lake Victoria, together with diatom and pollen data acquired from two nearby sites. According to the authors, the three coherent data sets revealed a “roughly 1400- to 1500-year spacing of century-scale P:E [precipitation: evaporation] fluctuations at Lake Victoria,” which “may be related to a ca. 1470-year periodicity in northern marine and ice core records that has been linked to solar variability (Bond *et al.*, 1997; Mayewski *et al.*, 1997).”

Further support of Stager *et al.*’s thesis comes from Verschuren *et al.* (2000), who developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on lake-level and salinity fluctuations of a small crater-lake basin in Kenya, as reconstructed from sediment stratigraphy and the species compositions of fossil diatom and midge assemblages. They compared this history with an equally long record of atmospheric $^{14}\text{CO}_2$ production, which is a proxy for solar radiation variations.

They found equatorial east Africa was significantly drier than today during the Medieval Warm Period from AD 1000 to 1270 and relatively wet during the Little Ice Age from AD 1270 to 1850. This latter period was interrupted by three periods of prolonged dryness: 1390–1420, 1560–1625, and 1760–1840. These “episodes of persistent aridity,” in the words of the authors, were “more severe than any recorded drought of the twentieth century.” They note their results “corroborate findings from north-temperate dryland regions that instrumental climate records are inadequate to appreciate the full range of natural variation in drought intensity at timescales relevant to socio-economic activity.” Today, almost every new storm of significant size, every new flood, or every new hint of drought almost anywhere in the world brings claims the weather is becoming more extreme than ever before as a consequence of global warming. Verschuren *et al.* remind us there were more intense droughts in the centuries preceding the recent rise in the atmosphere’s CO_2 content.

Verschuren *et al.* discovered “all three severe drought events of the past 700 years were broadly

coeval with phases of high solar radiation, and the intervening periods of increased moisture were coeval with phases of low solar radiation.” They state variations in solar radiative output “may have contributed to decade-scale rainfall variability in equatorial east Africa.” This conclusion is characterized as robust by Oldfield (2000), who suggests their results “provide strong evidence for a link between solar and climate variability.”

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3.4.4 Asia & Australia

Pederson *et al.* (2001) utilized tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for this region over the period 1651–1995.

Analyses of both standard deviations and five-year intervals of extreme wet and dry periods revealed “variations over the recent period of instrumental data are not unusual relative to the prior record” (see Figure 3.4.4.1). The authors state, however, the reconstructions “appear to show more frequent extended wet periods in more recent decades,” but they note this observation “does not demonstrate unequivocal evidence of an increase in

precipitation as suggested by some climate models.” More important to the present discussion, however, is their observation that spectral analysis of the data revealed significant periodicities of around 12 and 20–24 years, suggesting “possible evidence for solar influences in these reconstructions for northeastern Mongolia.”

Tan *et al.* (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau’s northeast margin since AD 960 based on an analysis of Chinese historical records, which they compared with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories. They found “high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere.” They also found “good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record.” These findings harmonize, in their words, with “numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene,” citing 22 scientific references. The researchers conclude the “synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity.”

Paulsen *et al.* (2003) utilized “high-resolution records of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in stalagmite SF-1 from Buddha Cave [33°40’N, 109°05’E] ... to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions.” They identified several major climatic episodes, including the Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and twentieth century warming, “lending support to the global extent of these events.” With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet, 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 Current Warm Period. Some of the Current Warm Period’s variability is undoubtedly due to the much finer one-year time resolution of the past 150 years of the record as compared to the three- to four-year resolution of the prior 1,120 years. The major droughts centered on AD 1835, 1878, and 1955 were very well delineated by this improved resolution.

Solar Forcing of Climate

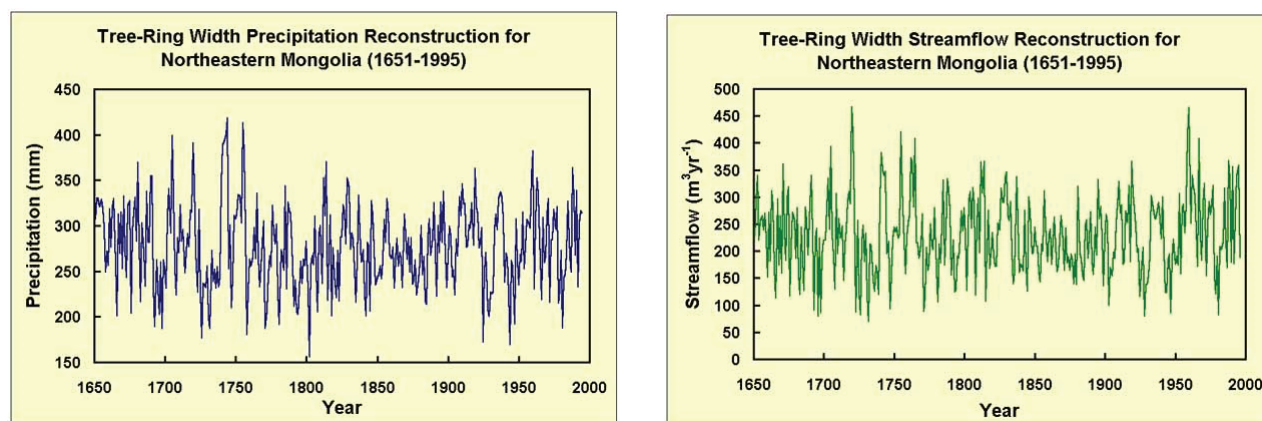


Figure 3.4.4.1. Reconstructed precipitation and streamflow records for northeastern Mongolia over the period 1651-1995. Adapted from Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651-1995. *Journal of Climate* **14**: 872–881.

The data also revealed a number of other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture. Paulsen *et al.* attributed most of these higher-frequency cycles to cyclical solar and lunar phenomena, concluding the summer monsoon over eastern China, which brings the region much of its precipitation, may “be related to solar irradiance.”

Liu *et al.* (2012) point out “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.” 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).

Liu *et al.* 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 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.” In addition, 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 note, “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.” Liu *et al.*’s analysis suggests precipitation in China’s Guangdong Province has become both less extreme and less variable during the 1956–2000 global warming.

Two recent papers by Zhao *et al.* (2012) and Wang and Zhao (2012), scientists at the National Satellite Meteorological Center of China Meteorological Administration, offered practical insights using instrumental records to consider the relationship between solar activity and precipitation. They studied all precipitation records across the whole of China covering all monthly data series but found robust correlations only for the month of June and for specific regions. Wang and Zhao (2012) report:

Six different statistical methods (i.e., correlation, difference, prominent period, variance contribution, scale-averaged spectrum, and cross spectrum) are used to test for regional differences in the relationship between the 11 year sunspot cycle and June precipitation in China during the 20th century. In the Huaihe River basin (HRB) of central China, located at the marginal region of

the East Asian summer monsoon (EASM), there exists a reliable positive-correlation relationship between the 11 year sunspot cycle and June precipitation; whereas, possible negative and very weak positive correlations in the south of the middle-lower Yangtze River Region and the HeTao Basin (HTB), located in the interior of the EASM and the westerlies, respectively. The reasons for these regional differences are investigated, revealing that the marginal region of EASM may be more sensitive to solar forcing than is its interior, which results in the HRB becoming the most susceptible (strongest correlation) region. That is to say, in June during the high sunspot number (SSN) years, the influence of the EASM is significantly greater and more to the north than that in June during the low SSN years, causing the HRB to be mainly influenced by the EASM (westerlies) in June during the high (low) SSN years. The northward expansion of the June EASM probably resulted from enhancement of the low-level southwesterly monsoon flow over the northern tropical Indian Ocean, combined with an expansion of the western Pacific subtropical high at times of high SSN.

Further research confirms the solar-climate link with respect to precipitation. In China's Taklimakan Desert, oases blossomed in sync with solar millennial scale cycles (Zhao *et al.*, 2012), and temperatures on the Tibetan plateau followed the sun's moods (Liu *et al.*, 2011). Yu *et al.* (2012) found the East Asian monsoon to be controlled by solar activity changes, while Wu *et al.* (2012) found water currents of the East China Sea varied according to the sun's behavior. The climate of the Baikal Lake was shown by Murakami *et al.* (2012) to be correlated with solar activity, and the rains in Southeast Australia were in sync with the solar pattern (Kemp *et al.*, 2012). Natural climate cycles appear to have led to the collapse of the powerful Indus Civilization (Giosan *et al.*, 2012).

The Indian monsoons have strengthened and weakened according to the rhythm of the sun over the past 150 years (van Loon and Meehl, 2012). Rains on the Tibetan Plateau stopped whenever the sun weakened (Sun and Liu, 2012). Corals in Japan died during cold phases triggered by low solar activity (Hamanaka *et al.*, 2012). A marked solar influence on Japanese climate was found in studies by Yamaguchi *et al.* (2010) and Muraki *et al.* (2011). Wet phases in Lake Aral were associated with solar high activity phases (Huang *et al.*, 2011).

Precipitation in Asia clearly is determined by

cycles, many of which are solar-driven and nearly all of which are independent of the air's CO₂ concentration.

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3.4.5 Europe

Mauquoy *et al.* (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes

of climate change during the Holocene. They report “analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al.* (1995), van Geel *et al.* (1996), Speranza *et al.* (2000), Speranza (2000) and Mauquoy *et al.* (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977).” This close correspondence suggests “changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al.*, 1996, 1998, 1999, 2000) and the ‘Little Ice Age’ series of palaeoclimatic changes.”

With respect to how the Sun may have driven the changes, the European scientists suggest two possibilities: “increased cosmic ray intensity, stimulating cloud formation and precipitation (Svensmark and Friis-Christensen, 1997),” and “reduced solar UV intensity, causing a decline of stratospheric ozone production and cooling as a result of less absorption of sunlight (Haigh, 1996, 2001).” Noting “modeling results of Shindell *et al.* (2001) suggest solar-induced variations of ozone production could drive temperature changes in the middle and lower atmospheres, which in turn could cause changes in the North Atlantic Oscillation and the Arctic Oscillation,” they tentatively conclude the solar UV mechanism may be the more likely of the two possibilities.

Blaauw *et al.* (2004) point out “Raised bogs are dependent on precipitation alone for water and nutrients,” and each of the species of plants found in them have specific requirements with respect to depth of water table. As a result, the vertical distribution of macro- and micro-fossils in raised bogs reveals much about past changes in local moisture conditions, especially, the authors note, “about changes in effective precipitation (precipitation minus evapotranspiration).” At the same time, changes in the carbon-14 content of bog deposits reveal something about solar activity, because, as Blaauw *et al.* describe the connection, “a decreased solar activity leads to less solar wind, reduced shielding against cosmic rays, and thus to increased production of cosmogenic isotopes [such as ^{14}C].” Consequently, it is possible to compare the histories of the two records (effective precipitation and $\delta^{14}\text{C}$) and see if inferred changes in climate bear any relationship to inferred

changes in solar activity.

Two cores of mid-Holocene raised-bog deposits in the Netherlands were ^{14}C “wiggle-match” dated by the authors at high precision, using the technique described by Kilian *et al.* (1995, 2000) and Blaauw *et al.* (2003), and changes in local moisture conditions were inferred from the changing species composition of consecutive series of macrofossil samples. They found nine of 11 major mid-Holocene $\delta^{14}\text{C}$ increases, “probably caused by declines in solar activity,” were coeval with major wet-shifts “probably caused by climate getting cooler and/or wetter.” In the case of the significant wet-shift at the major $\delta^{14}\text{C}$ rise in the vicinity of 850 BC, they note this prominent climatic cooling has been independently documented in many parts of the world, including “the North Atlantic Ocean (Bond *et al.*, 2001), the Norwegian Sea (Calvo *et al.*, 2002) [see also Andersson *et al.* (2003)], Northern Norway (Vorren, 2001), England (Waller *et al.*, 1999), the Czech Republic (Speranza *et al.*, 2000, 2002), central southern Europe (Magny, 2004), Chile (van Geel *et al.*, 2000), New Mexico (Armour *et al.*, 2002) and across the continent of North America (Viau *et al.*, 2002).”

Blaauw *et al.* (2003) say their findings “add to the accumulating evidence that solar variability has played an important role in forcing climatic change during the Holocene.”

Cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen) by Björck and Clemmensen (2004) were examined for their content of wind-transported clastic material via a systematic count of quartz grains of diameter 0.2–0.35 mm and larger than 0.35 mm to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter storminess in that part of the world. According to the authors, “the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia.” They note “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,” while “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 specifically 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, an event of increased storminess they dated to AD 1650 “falls at the beginning of the Maunder solar minimum (AD 1645–1715),” while high ASI values between AD 1450 and 1550 with “a very distinct peak at AD 1475” coincide with the Spörer Minimum of AD 1420–1530. The latter three peaks in winter storminess, they note, all occurred during the Little Ice Age and “are among the most prominent in the complete record.”

Several researchers have studied the precipitation histories of regions along the Danube River in western Europe and their effects on river discharge, with some suggesting an anthropogenic signal is present in the latter decades of the twentieth century and is responsible for that period’s drier conditions. Ducic (2005) examined such claims by analyzing observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He notes the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was practically equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. In addition, the discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be “completely inside the limits of the whole series” and only slightly ($38 \text{ m}^3\text{s}^{-1}$ or 0.7 percent) less than the 260-year mean of $5356 \text{ m}^3\text{s}^{-1}$. Ducic concludes “modern discharge fluctuations do not point to [a] dominant anthropogenic influence.” His correlative analysis suggests the detected cyclicity in the record could “point to the domination of the influence of solar activity.”

Holzhauser *et al.* (2005) present 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 temperature

and precipitation climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest of all glaciers located in the European Alps.

Near the beginning of the 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, they state, “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 followed by “the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300.” They note 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,” following which the glacier began its latest and still-ongoing recession in 1865.

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, 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 Karlén, 1973; Magny, 1993; van Geel *et al.*, 1996; Bond *et al.*, 2001).” They conclude by stating “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.”

Lamy *et al.* (2006) used paleoenvironmental proxy data for ocean properties, eolian sediment input, and continental rainfall based on high-resolution analyses of sediment cores from the southwestern Black Sea and the northernmost Gulf of Aqaba to infer hydroclimatic changes in northern

Anatolia and the northern Red Sea region during the last ~7500 years. That reconstructed hydroclimatic history was compared with $\Delta^{14}\text{C}$ periodicities evident in the tree-ring data of Stuiver *et al.* (1998). The researchers found “pronounced and coherent” multicentennial variations they conclude “strongly resemble modern temperature and rainfall anomalies related to the Arctic Oscillation/North Atlantic Oscillation (AO/NAO).” In addition, they state “the multicentennial variability appears to be similar to changes observed in proxy records for solar output changes,” although “the exact physical mechanism that transfers small solar irradiance changes either to symmetric responses in the North Atlantic circulation or to atmospheric circulation changes involving an AO/NAO-like pattern, remains unclear.”

In 2012 Dermody *et al.* found solar-driven millennial scale cycles controlled wet and drought phases in the Mediterranean region during Roman times.

Each of these studies indicates cyclical solar activity induces cyclical precipitation activity in Europe. As Lamy *et al.* (2006) note, “the impact of (natural) centennial-scale climate variability on future climate projections could be more substantial than previously thought.”

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3.5 Other Climatic Variables

In the previous two sections of this chapter we examined empirical observations of a solar influence on temperature and precipitation. In this section we examine empirical observations of the Sun's influence on other climate variables, including droughts, floods, monsoons, and streamflow.

3.5.1 Droughts

The IPCC claims Earth's climate is becoming more variable and extreme as a result of CO₂-induced global warming, and it forecasts increasing length and severity of drought as one of the consequences. In Chapter 7 of this report, addressing extreme weather, we will present evidence that modern drought frequency and severity fall well within the range of natural variability. Here, we consider the issue of

attribution, specifically investigating the natural influence of the Sun on drought. We begin with a review of the literature on droughts in the United States.

According to Cook *et al.* (2007), recent advances in the reconstruction of past drought periods over North America “have revealed the occurrence of a number of unprecedented megadroughts over the past millennium that clearly exceed any found in the instrumental records.” They state “these past megadroughts dwarf the famous droughts of the twentieth century, such as the Dust Bowl drought of the 1930s, the southern Great Plains drought of the 1950s, and the current one in the West that began in 1999.” These dramatic droughts pale when compared to “an epoch of significantly elevated aridity that persisted for almost 400 years over the AD 900–1300 period,” they write.

Of central importance to North American drought formation “is the development of cool ‘La Niña-like’ SSTs in the eastern tropical Pacific,” the note. Paradoxically, as they describe the situation, “warmer conditions over the tropical Pacific region lead to the development of cool La Niña-like SSTs there, which is drought inducing over North America.” In further explaining the mechanics of this phenomenon, on which both “model and data agree,” Cook *et al.* state, “if there is a heating over the entire tropics then the Pacific will warm more in the west than in the east because the strong upwelling and surface divergence in the east moves some of the heat poleward”; as a result, “the east-west temperature gradient will strengthen, so the winds will also strengthen, so the temperature gradient will increase further, ... leading to a more La Niña-like state.” They add “La Niña-like conditions were apparently the norm during much of the Medieval period when the West was in a protracted period of elevated aridity and solar irradiance was unusually high.”

Yu and Ito (1999) studied a sediment core from a closed-basin lake in the northern Great Plains of North America, producing a 2,100-year record that revealed four dominant periodicities of drought matching “in surprising detail” similar periodicities of various solar indices. The correspondence was so close, they state “this spectral similarity forces us to consider solar variability as the major cause of century-scale drought frequency in the northern Great Plains.”

Dean and Schwalb (2000) derived a similar-length record of drought from sediment cores extracted from Pickerel Lake, South Dakota, which

also exhibited recurring incidences of major drought on the northern Great Plains. They too reported the cyclical behavior appeared to be synchronous with variations in solar irradiance. After making a case for “a direct connection between solar irradiance and weather and climate,” they conclude “it seems reasonable that the cycles in aridity and eolian activity over the past several thousand years recorded in the sediments of lakes in the northern Great Plains might also have a solar connection.”

Springer *et al.* (2008) derived a multidecadal-scale record of Holocene drought based on Sr/Ca ratios and $\delta^{13}\text{C}$ data obtained from stalagmite BCC-002 from Buckeye Creek Cave (BCC), West Virginia (USA) that “grew continuously from ~7000 years B.P. to ~800 years B.P.” and then again “from ~800 years B.P. until its collection in 2002.”

They identified seven significant mid- to late-Holocene droughts, six of which “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” (see Bond *et al.*, 2001). In addition, they determined the Sr/Ca and $\delta^{13}\text{C}$ time series “display periodicities of ~200 and ~500 years and are coherent in those frequency bands.” They also state, “the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle,” and they “interpret the ~500-year periodicity to be a harmonic of the IRD oscillations.” Noting “cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years,” they observe “these latter values are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500 -years IRD periodicity.” The five researchers conclude their 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),” adding their high-resolution time series now provide even stronger evidence “in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results.”

Mensing *et al.* (2004) inferred the hydrological history of the Pyramid Lake, Nevada area by analyzing a set of sediment cores for pollen and algal microfossils deposited in the lake over the past 7,630 years. According to the authors, “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, they found, “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.” They note “the timing and magnitude of droughts identified in the pollen record compares 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.” They compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice (Bond *et al.*, 2001) and, like other researchers, found “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.* conclude “changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States].”

Asmerom *et al.* (2007) developed a high-resolution climate proxy for the southwest United States from $\delta^{18}\text{O}$ variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw $\delta^{18}\text{O}$ data revealed significant peaks the researchers say “closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993).” They report cross-spectral analysis of the $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar link to Holocene climate operates “through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean.”

Hodell *et al.* (2001) analyzed sediment cores obtained from Lake Chichancanab on the Yucatan Peninsula of Mexico, reconstructing the climatic history of this region over the past 2,600 years. Long episodes of drought were noted throughout the record, and spectral analysis revealed a significant periodicity that matched well with a cosmic ray-produced ^{14}C

record preserved in tree rings believed to reflect variations in solar activity. They concluded “a significant component of century-scale variability in Yucatan droughts is explained by solar forcing.”

Black *et al.* (1999) found evidence of substantial decadal and centennial climate variability in a study of ocean sediments deposited in the southern Caribbean over the past 825 years. Their data suggest climate regime shifts are a natural aspect of Atlantic variability. They conclude “these shifts may play a role in triggering changes in the frequency and persistence of drought over North America.” Because there was a strong correspondence between these phenomena and similar changes in ^{14}C production rate, they conclude “small changes in solar output may influence Atlantic variability on centennial time scales.”

Helama *et al.* (2009) used regional curve standardization (RCS) procedures with data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland 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),” from AD 670 to AD 1993. They find “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.” This interval, they write, “precisely overlaps the period commonly referred to 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 they discovered “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, 2005a, 2007; Stager *et al.*, 2005) between AD 900 and 1300.” Noting this widespread evidence “argues for a common force behind the hydrological component of the MCA,” they note “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),” stating “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).”

Verschuren *et al.* (2000) conducted a similar study of a small lake in Kenya, documenting the existence of three periods of prolonged dryness during the Little Ice Age that were, in their words, “more severe than any recorded drought of the twentieth century.” They discovered all three of these severe drought events “were broadly coeval with phases of high solar radiation,” as inferred from ^{14}C production data, “and the intervening periods of increased moisture were coeval with phases of low solar radiation.” They concluded variations in solar activity “may have contributed to decade-scale rainfall variability in equatorial east Africa.”

Also in Africa, working with three sediment cores extracted from Lake Edward (0°N, 30°E), Russell and Johnson (2005b) developed a continuous 5,400-year record of Mg concentration and isotopic composition of authigenic inorganic calcite as proxies for the lake’s water balance, which is itself a proxy for regional drought conditions in equatorial Africa. They found “the geochemical record from Lake Edward demonstrates a consistent pattern of equatorial drought during both cold and warm phases of the North Atlantic’s ‘1500-year cycle’ during the late Holocene,” noting similar “725-year climate cycles” are found in several records from the Indian and western Pacific Oceans and the South China Sea, citing the studies of von Rad *et al.* (1999), Wang *et al.* (1999), Russell *et al.* (2003), and Staubwasser *et al.* (2003). Russell and Johnson state their results “show that millennial-scale high-latitude climate events are linked to changes in equatorial terrestrial climate ... during the late Holocene” and “suggest a spatial footprint in the tropics for the ‘1500-year cycle’ that may help to provide clues to discern the cycle’s origin,” noting there is reason to believe it may be solar-induced.

Garcin *et al.* (2007) explored hydrologic change using late-Holocene paleoenvironmental data derived from several undisturbed sediment cores retrieved from the deepest central part of Lake Masoko (9°20.0’S, 33°45.3’E), which occupies a maar crater in the Rungwe volcanic highlands of the western branch of Africa’s Rift Valley, approximately 35 km north of Lake Malawi. According to the ten

researchers, “magnetic, organic carbon, geochemical proxies and pollen assemblages indicate a dry climate during the ‘Little Ice Age’ (AD 1550–1850), confirming that the LIA in eastern Africa resulted in marked and synchronous hydrological changes,” although “the direction of response varies between different African lakes.”

They report “to the south (9.5–14.5°S), sediment cores from Lake Malawi have revealed similar climatic conditions (Owen *et al.*, 1990; Johnson *et al.*, 2001; Brown and Johnson, 2005)” “correlated with the dry period of Lakes Chilwa and Chiuta (Owen and Crossley, 1990).” They further note “lowstands have been also observed during the LIA at Lake Tanganyika ... from AD 1500 until AD 1580, and from ca. AD 1650 until the end of the 17th century, where the lowest lake-levels are inferred (Cohen *et al.*, 1997; Alin and Cohen, 2003).” By contrast, they report “further north, evidence from Lakes Naivasha (0.7°S) and Victoria (2.5°S–0.5°N) indicates relatively wet conditions with high lake-levels during the LIA, interrupted by short drought periods (Verschuren *et al.*, 2000; Verschuren, 2004; Stager *et al.*, 2005).”

Garcin *et al.* also note, “inferred changes of the Masoko hydrology are positively correlated with the solar activity proxies.” The African and French scientists say the Little Ice Age in Africa appears to have had a greater thermal amplitude than it did in the Northern Hemisphere, citing in support of this statement the paleoclimate studies of Bonnefille and Mohammed (1994), Karlén *et al.* (1999), Holmgren *et al.* (2001), and Thompson *et al.* (2002). Nevertheless, the more common defining parameter of the Little Ice Age in Africa was the moisture status of the continent, which appears to have manifested opposite directional trends in different latitudinal bands. In addition, the group of scientists emphasizes the positive correlation of Lake Masoko hydrology with various solar activity proxies “implies a forcing of solar activity on the atmospheric circulation and thus on the regional climate of this part of East Africa.”

Trouet *et al.* (2009) describe in *Science* 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), “a period (~ AD 800–1300) marked by a wide range of changes in climate

globally.” This interval of medieval warmth, as they describe it, 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 shown in Figure 3.5.1.1. The peak strength of the NAO during the MCA is shown to have been essentially equivalent to the peak strength the NAO has so far manifested during the Current Warm Period (CWP). This finding suggests the peak warmth of the MCA was also likely equivalent to the peak warmth of the CWP.

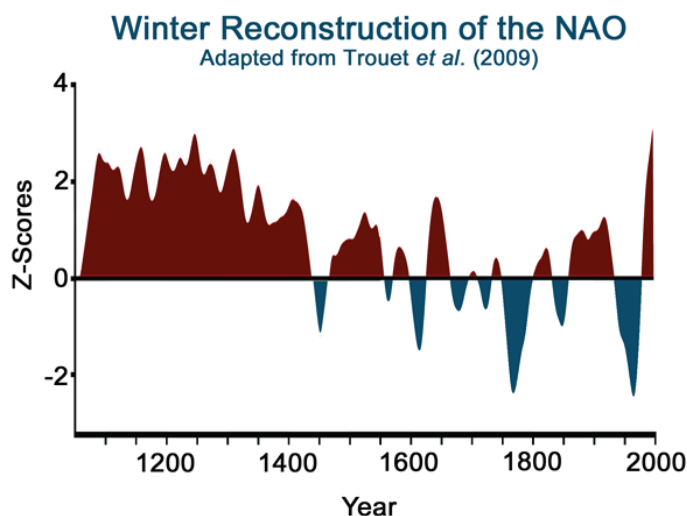


Figure 3.5.1.1. Winter reconstruction of the NAO for the period AD 1049–1995 based on a tree-ring-proxy drought reconstruction for Morocco and a speleothem-based precipitation proxy for Scotland. Adapted from Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* 324: 78–80.

To explain their findings, Trouet *et al.* propose “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.” What initiated these phenomena? Trouet *et al.* write, “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 irradiance and/or reduced volcanic activity and amplified and prolonged by enhanced AMOC.”

Barker’s (2008) analysis of data from 1876 to the present suggests when the Sun’s South Pole is positive in the Hale Cycle, the likelihood of strongly positive and negative Southern Oscillation Index (SOI) values increase after certain phases in the cyclic ~22-year solar magnetic field. The SOI is also shown to track the pairing of sunspot cycles in ~88-year periods. This coupling of odd cycles—23–15, 21–13, and 19–11—produces an apparently close charting of positive and negative SOI fluctuations for each grouping. This Gleissberg effect is also apparent in the southern hemisphere rainfall anomaly. Over the past decade, the SOI and rainfall fluctuations have been tracking values similar to those recorded in Cycle 15 (1914–1924). This discovery may have important implications for future drought predictions in Australia and in countries in the Northern and Southern Hemisphere, which have been shown to be influenced by the sunspot cycle. Further, it provides a benchmark for long-term SOI behaviour.

There seems to be little question that variations in solar activity have been responsible for much of the drought variability of the Holocene in many parts of the world.

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3.5.2 Floods

The IPCC claims floods will become more variable and extreme as a result of CO₂-induced global warming. In Chapter 7 of this report, addressing extreme weather, we report peer-reviewed research showing modern flood frequency and severity fall well within the range of natural variability. Here we limit our examination once again to the issue of attribution, specifically investigating the influence of the Sun on floods.

We begin by reviewing what is known about the relationship of extreme weather events to climate in Europe during the Holocene. According to Starkel (2002), in general, more extreme fluvial activity, of both the erosional and depositional type, is associated with cooler climates. “Continuous rains and high-intensity downpours,” writes Starkel, were most common during the Little Ice Age. Such “flood phases,” the researcher reports, “were periods of very

unstable weather and frequent extremes of various kinds.” Starkel also notes “most of the phases of high frequency of extreme events during the Holocene coincide with the periods of declined solar activity.”

In 2010, Markus Czymzik and colleagues published an important article on flooding in the journal of *Water Resources Research* (Czymzik *et al.* 2010). The German and French scientists present the flood frequency development of Lake Ammersee (Bavaria’s third largest lake) for the past 450 years. They observed an excellent correlation with solar activity as depicted in Figure 3.5.2.1. When solar activity was weak, flooding increased at Lake Ammersee. This relationship also was demonstrated in a February 2013 paper in *Quaternary Science Reviews* (Czymzik *et al.* 2013).

Noren *et al.* (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km² region in Vermont and eastern New York (USA), after which several techniques were used to identify and date terrigenous in-wash layers depicting the frequency of storm-related floods. The analysis showed “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.” Four major storminess peaks were identified, approximately 2.6, 5.8, 9.1, and 11.9 kyr ago, with the most recent upswing in storminess beginning “at about 600 yr BP [before present], coincident with the beginning of the Little Ice Age.” Noren *et al.* state the pattern they observed “is consistent with long-term changes in the average sign of the Arctic Oscillation [AO],” further suggesting “changes in the AO, perhaps modulated by solar forcing, may explain a significant portion of Holocene climate variability in the North Atlantic region.”

Schimmelmann *et al.* (2003) identified conspicuous gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, which they accurately dated by varve-counting. Analysis of the record revealed six prominent flood events occurring 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

Climate Change Reconsidered II

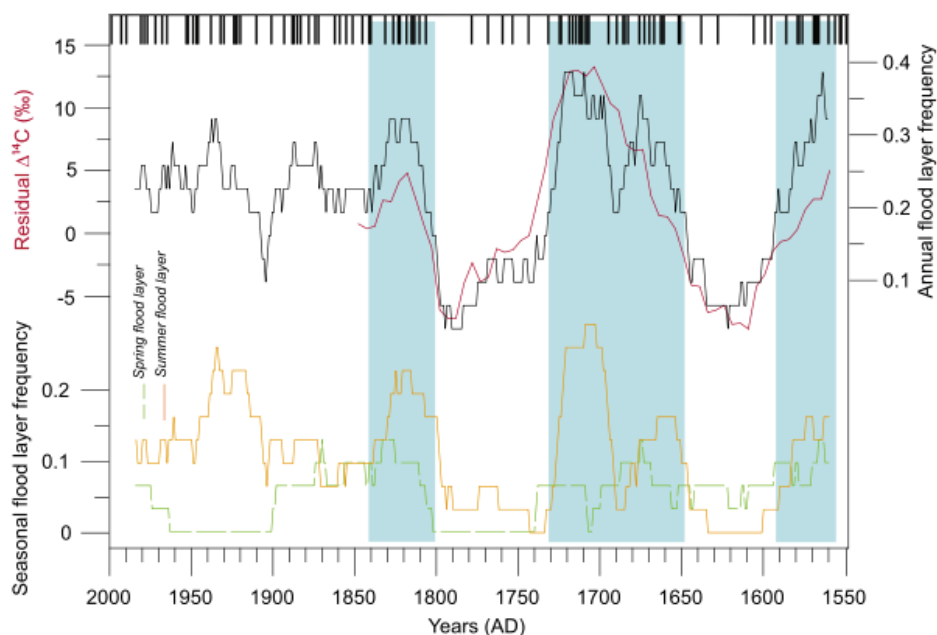


Figure 3.5.2.1. Flooding frequency of the Lake Ammersee region (bottom) and solar activity (above). Phases of minimal solar activity are shown with a blue shaded background. Whenever the sun was weak (high ^{14}C values, peak) flooding was more frequent. Reprinted with permission from Cyzmik, M., Dulski, 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**: 379-395, 10.1029/2009WR008360.

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).’’

Schimmelmann *et al.* also note “the quasi-periodicity of ~200 years for southern California floods matches the ~200-year periodicities found in a variety of high-resolution palaeoclimate archives and, more importantly, a *c.*208-year cycle of solar activity and inferred changes in atmospheric circulation.” They “hypothesize that 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.”

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3.5.3 Monsoons

The IPCC's computer models fail to predict variability in monsoon weather, at least partly because they underestimate the Sun's role.

The Indian Summer Monsoon (ISM) and its associated local and regional patterns of rainfalls are among the most notoriously complex expressions of the tropical Earth's coupled land, ocean, and atmosphere system. The densely populated countries of South Asia depend critically on the rain water brought on by the ISM during the four summer months from June to September, which is why scientists are keenly interested in understanding the underlying factors responsible for the climatological and anomalous variations of the ISM rainfalls. They have identified a host of factors related to the ISM, from the quasi-biennial oscillation of the equatorial stratospheric winds, ENSO, Eurasian snow cover, conditions of the Indo-Pacific warm pool and Indian subcontinent, and sunspot activity. The pursuit of how the Sun's magnetic activity may modulate the ISM rainfall has been filled with many false starts and promises.

Figure 3.5.3.1 shows the surprising correlations between the All-India and Konkan-Goa regional rainfalls and the new solar forcing index of the derivative of the Total Solar Irradiance (TSI) reported in Agnihotri *et al.* (2011).

Noting many of the weaknesses in previous solar-ISM studies that adopted sunspot numbers or the 10.7 cm solar radio radiation flux, Agnihotri *et al.* (2011) adopt the time-derivative of TSI as a more relevant physical parameter for a better exploration of how the intrinsic solar radiative forcing of the Sun can modulate the ISM rainfall on multidecadal timescales. Van Loon and Meehl (2012) added further insights by arguing for the use of sunspot peaks as another useful metric for a physical investigation of solar-ISM relationship.

The results shown in Figure 3.5.3.1 suggest more severe drought conditions generally prevail during periods of steadily falling TSI or less solar radiation energy added to the Earth system. Periods of positive

TSI derivative correspond to periods of anomalous excess of ISM rainfall, although the TSI derivative-rainfall relationship is clearly nonlinear and not fully symmetrical for solar-forcing-induced wet-dry oscillations and transitions.

Figure 3.5.3.2 adds more confidence to the empirical correlation of solar modulation of instrumental ISM rainfall shown in Figure 3.5.3.1 by extending the correlation back to 1700 AD, an additional 150 years of data record. Agnihotri *et al.* (2011) adopted the high-quality rainfall proxy data set obtained from the speleothem $\delta^{18}\text{O}$ data from Akalagavi cave located in the hills of the western Ghats mountain range in the southwestern state of Karnataka.

Figure 3.5.3.3 reveals a social dimension to the negative TSI derivative-related dry periods, severe drought, and even major famine (death toll greater than 1 million people) events recorded in all three data sets from instrumental, historical, and proxy records. The statistics from Figure 3.5.3.3 show four of seven major famines recorded in Indian subcontinent history fall near negative TSI derivatives. For example, the “terrible” famine of 1876–1879 that killed an estimated 10 million people (the death was not strictly from starvation alone; outbreaks of cholera were also a known factor) spread across nearly the whole of southern, western, and northern India and was associated with the most negative TSI derivative values constructed. The TSI derivative proxy is also able to pick up the famine events of 1896–1897 and 1899–1902 in which the estimated death tolls ranged from 8.4 to 19 million.

Agnihotri *et al.* (2011) attempted to explain the empirical correlations determined from real-world data (instrumental and proxy) by suggesting the differential addition or subtraction of solar energy to relatively cloud-free regions in the southern Indian ocean “would probably cause warm-pool sea surface conditions and atmospheric convective activity to vary in synchrony with the observed large-scale changes in the summer monsoonal circulation and rainfall in the Indian subcontinent.” A positive (negative) TSI derivative phase corresponded to both enhanced (reduced) surface evaporation and an overall increase (decrease) in convective velocity, which in turns leads to the enhanced (reduced) southwest monsoonal circulation and increased (decreased) All-India and Konkan-Goa rainfalls, as observed in Figures 3.5.3.2 and 3.5.3.3.

Neff *et al.* (2001) investigated the relationship between a ^{14}C tree-ring record and a $\delta^{18}\text{O}$ proxy

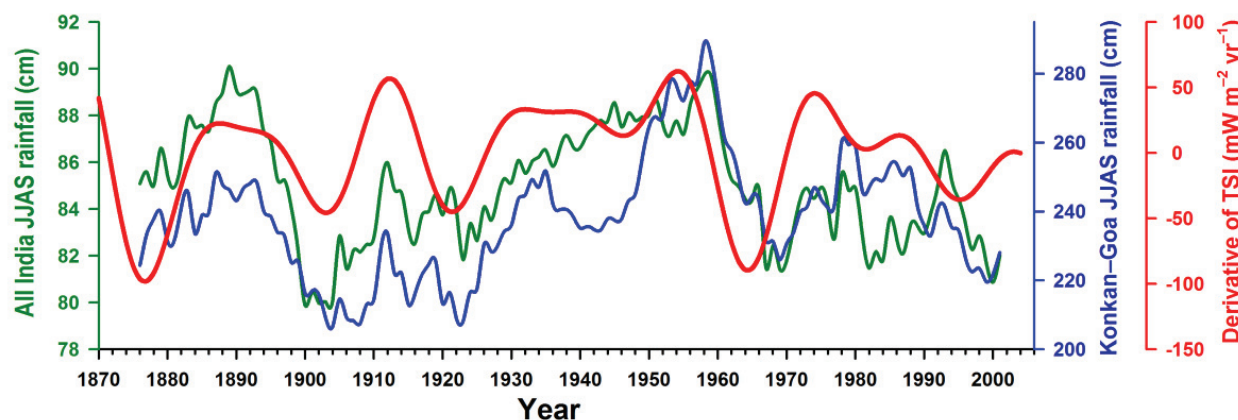


Figure 3.5.3.1. The All Indian Monsoon and Konkan-Goa Regional Monsoon rainfalls are correlated with the temporal derivative of the TSI offering new insights into a plausible solar modulation of the Indian summer monsoon rainfall variability on a multidecadal timescale. Reprinted with permission from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* 73: 1980–1987.

record of monsoon rainfall intensity for the period 9,600–6,100 years before present, as recorded in calcite $\delta^{18}\text{O}$ data obtained from a stalagmite in northern Oman. The authors found the correlation between the two data sets to be “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 tree-ring records are generally attributed to variations in solar activity and intensity, and because this particular ^{14}C record was strongly correlated with the $\delta^{18}\text{O}$ record as well as the closely corresponding results of the spectral analyses, the authors conclude there is “solid evidence” that both signals (the ^{14}C and $\delta^{18}\text{O}$ records) are responding to solar forcing.

Similar findings were reported by Lim *et al.* (2005), who examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, creating a 6,500-year proxy record of major Asian dust events produced by northwesterly winter monsoonal winds that carry dust from the inner part of China all the way to Korea and the East China Sea. The Asian dust time series was found to contain both millennial- and centennial-scale periodicities; cross-spectral analysis between the EQC and a solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the researchers to conclude centennial-scale periodicities

in the EQC could be ascribed primarily to fluctuations in solar activity.

Ji *et al.* (2005) used reflectance spectroscopy on a sediment core taken from Qinghai Lake in the northeastern part of the Qinghai-Tibet Plateau to construct a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. Monsoonal moisture since the late glacial period was shown to be subject to “continual and cyclic variations,” including the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age, which lasted from 2,100 to 1,800 yr BP and 780 to 400 yr BP, respectively. Sandwiched between them was the warmer and wetter Medieval Warm Period, while preceding the DACP was the Roman Warm Period. Time series analysis of the sediment record revealed statistically significant periodicities (above the 95 percent level) of 123, 163, 200, and 293 years. The third of these periodicities corresponds well with the de Vries or Suess solar cycle, suggesting cyclical changes in solar activity are important triggers for some of the cyclical changes in monsoon moisture at Qinghai Lake.

Citing studies that suggest the Indian summer monsoon may be sensitive to changes in solar forcing of as little as 0.25 percent (Overpeck *et al.*, 1996; Neff *et al.*, 2001; Fleitmann *et al.*, 2003), Gupta *et al.* (2005) compared trends in the Indian summer monsoon with trends in solar activity across the Holocene. Temporal trends in the Indian summer

Solar Forcing of Climate

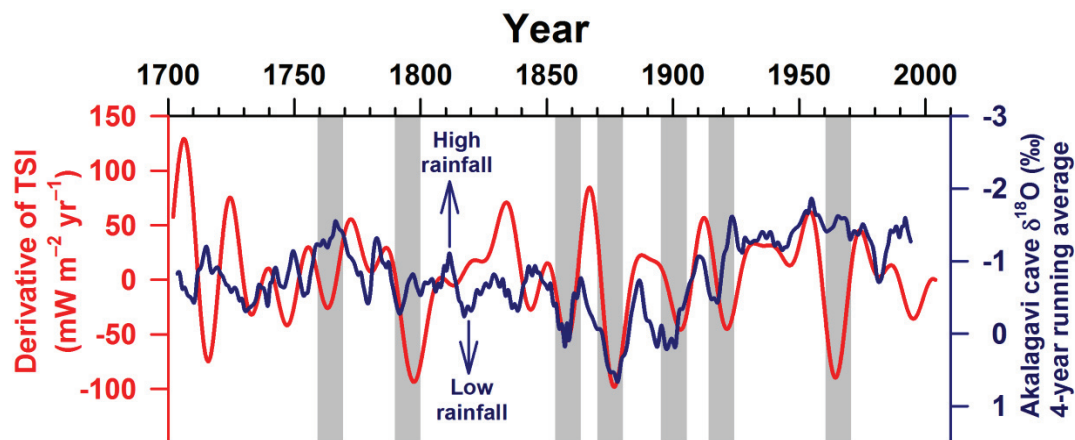


Figure 3.5.3.2. The solar modulation of the Indian summer monsoon rainfall variability on multidecadal timescale relation shown in Figure 3.5.3.1 above can be extended back to about 1700 AD using the rainfall proxy from Akalagavi Cave (located in southwestern India in the state of Karnataka) speleothem $\delta^{18}\text{O}$ data series. Adapted from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* 73: 1980–1987.

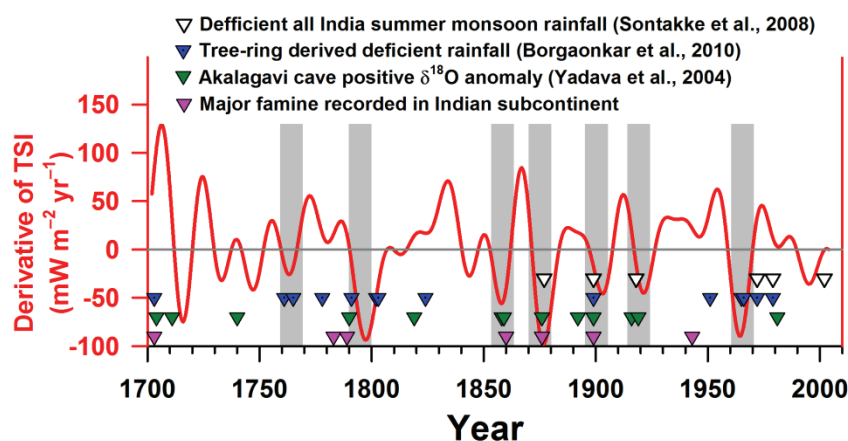


Figure 3.5.3.3. Major drought events from both instrumental and proxy datasets (both tree-ring and speleothem records) as well as major historical famine (death toll exceeding 1 million people) correspond roughly with intervals with low or most negative TSI derivatives (marked by gray vertical bars). Also adapted from Agnihotri *et al.* (2011).

monsoon were inferred from relative abundances of fossil shells of the planktic foraminifer *Globigerina bulloides* in sediments of the Oman margin, while temporal trends in solar variability were inferred from relative abundances of ^{14}C , ^{10}Be and haematite-stained grains.

Spectral analyses of the data sets revealed statistically significant periodicities in the *G. bulloides* time series centered at 1550, 152, 137, 114, 101, 89, 83, and 79 years; all but the first of these periodicities closely matched periodicities of sunspot numbers centered at 150, 132, 117, 104, 87, 82, and

75 years. Gupta *et al.* conclude this close correspondence provides strong evidence for a “century-scale relation between solar and summer monsoon variability.” In addition, they report intervals of monsoon minima correspond to intervals of low sunspot numbers, increased production rates of the cosmogenic nuclides ^{14}C and ^{10}Be , and increased advection of drift ice in the North Atlantic, such that over the past 11,100 years “almost every multi-decadal to centennial scale decrease in summer monsoon strength is tied to a distinct interval of reduced solar output,” and nearly every increase

“coincides with elevated solar output,” including a stronger monsoon (high solar activity) during the Medieval Warm Period and a weaker monsoon (low solar activity) during the Little Ice Age.

Gupta *et al.* consider the presence of the 1,550-year cycle in the Indian monsoon data to be “remarkable,” as this cycle has been identified in numerous climate records of both the Holocene and the last glacial epoch (including Dansgaard/Oeschger cycles in the North Atlantic), strengthening the case for a Sun-monsoon-North Atlantic link. The researchers say they are “convinced” there is a direct solar influence on the Indian summer monsoon in which small changes in solar output bring about pronounced changes in tropical climate.

Khare and Nigam (2006) examined variations in angular-asymmetrical forms of benthic foraminifera and planktonic foraminiferal populations in a shallow-water sediment core obtained off Kavar (14°49'43"N, 73°59'37"E) on the central west coast of India, which receives heavy river discharge during the southwest monsoon season (June to September) from the Kali and Gangavali rivers. Down-core plots of the data showed three major troughs separated by intervening peaks, and “since angular-asymmetrical forms and planktonic foraminiferal population are directly proportional to salinity fluctuations,” according to Khare and Nigam, “the troughs ... suggest low salinity (increased river discharge and thus more rainfall),” and “these wet phases are alternated by dry conditions.” They further report the dry episodes of higher salinity occurred in AD 1320–1355, 1445–1535, and 1625–1660; the wet phases were centered at approximately AD 1410, 1590, and 1750, close to the ending of the sunspot minima of the Wolf Minima (AD 1280–1340), the Spörer Minima (AD 1420–1540), and the Maunder Minima (AD 1650–1710), respectively.

Although Khare and Nigam state “providing a causal mechanism is beyond the scope of the present study,” they note “the occurrence of periods of enhanced monsoonal precipitation slightly after the termination of the Wolf, Spörer and Maunder minima periods (less Sun activity) and concomitant temperature changes could be a matter of further intense research.” The correspondences seem to be more than merely coincidental, especially when the inferences of the two researchers are said to be “in agreement with the findings of earlier workers, who reported high lake levels from Mono Lake and Chad Lake in the vicinity of solar minima,” as well as the Nile river in Africa, which “witnessed high level at

around AD 1750 and AD 1575.”

Tiwari *et al.* (2005) conducted a high-resolution (~50 years) oxygen isotope analysis of three species of planktonic foraminifera (*Globigerinoides ruber*, *Gs. Sacculifer*, and *Globarotalia menardii*) contained in a sediment core extracted from the eastern continental margin (12.6°N, 74.3°E) of the Arabian Sea, covering the past 13,000 years. Data for the final 1,200 years of this period were compared with the reconstructed total solar irradiance (TSI) record developed by Bard *et al.* (2000), based on fluctuations of ¹⁴C and ¹⁰Be production rates obtained from tree rings and polar ice sheets.

The researchers found the Asian Southwest Monsoon (SWM) “follows a dominant quasi periodicity of ~200 years, which is similar to that of the 200-year Suess solar cycle (Usokin *et al.*, 2003).” This finding indicates, in their words, “that SWM intensity on a centennial scale is governed by variation in TSI,” which “reinforces the earlier findings of Agnihotri *et al.* (2002) from elsewhere in the Arabian Sea.”

In considering the SWM/TSI relationship, the five researchers note “variations in TSI (~0.2%) seem to be too small to perturb the SWM, unless assisted by some internal amplification mechanism with positive feedback,” and they discuss two possible mechanisms. The first “involves heating of the Earth’s stratosphere by increased absorption of solar ultraviolet (UV) radiation by ozone during periods of enhanced solar activity (Schneider, 2005).” According to this scenario, more UV reception leads to more ozone production in the stratosphere, which leads to more heat being transferred to the troposphere, which leads to enhanced evaporation from the oceans, which finally enhances monsoon winds and precipitation. The second mechanism, as they describe it, is that “during periods of higher solar activity, the flux of galactic cosmic rays to the Earth is reduced, providing less cloud condensation nuclei, resulting in less cloudiness (Schneider, 2005; Friis-Christensen and Svensmark, 1997),” which then allows for “extra heating of the troposphere” that “increases the evaporation from the oceans.”

Dykoski *et al.* (2005) obtained high-resolution records of stable oxygen and carbon isotope ratios from a stalagmite recovered from Dongge Cave in southern China and developed a proxy history of Asian monsoon variability over the past 16,000 years. They discovered numerous centennial- and multidecadal-scale oscillations in the record up to half the amplitude of interstadial events of the last glacial

age, indicating “significant climate variability characterizes the Holocene.” Spectral analysis of $\delta^{14}\text{C}$ data revealed significant peaks at solar periodicities of 208, 86, and 11 years, which they say is “clear evidence that some of the variability in the monsoon can be explained by solar variability.”

Building on this work and that of Yuan *et al.* (2004), Wang *et al.* (2005) developed a shorter (9,000-year) but higher-resolution (4.5-year) absolute-dated $\delta^{18}\text{O}$ monsoon record for the same location, which they compared with atmospheric ^{14}C data and climate records from lands surrounding the North Atlantic Ocean. Their monsoon record broadly followed summer insolation but was punctuated by eight significantly weaker monsoon periods lasting from one to five centuries, most of which coincided with North Atlantic ice-rafting events. In addition, they found “cross-correlation of the decadal- to centennial-scale monsoon record with the atmospheric ^{14}C record shows that some, but not all, of the monsoon variability at these frequencies results from changes in solar output,” similar to “the relation observed in the record from a southern Oman stalagmite (Fleitmann *et al.*, 2003).”

In a news item by Kerr (2005) accompanying the report of Wang *et al.*, one of the report’s authors (Hai Cheng of the University of Minnesota) was quoted as saying their study suggests “the intensity of the summer [East Asian] monsoon is affected by solar activity.” Dominik Fleitman, who worked with the Oman stalagmite, also said “the correlation is very strong,” stating it is probably the best monsoon record he had seen, “even better than ours.” Gerald North of Texas A & M University, whom Kerr described as a “longtime doubter,” admitted he found the monsoon’s solar connection “very hard to refute,” although he stated “the big mystery is that the solar signal should be too small to trigger anything.”

Porter and Weijian (2006) used 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers “represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation,” while “brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate.”

The most recent of the episodic cold periods, which Porter and Weijian identify as the Little Ice Age, began about AD 1370, and the preceding cold period ended somewhere in the vicinity of AD 810. Consequently, their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. They also report the climatic variations they discovered “correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water.” This correlation implies solar forcing (see Bond *et al.*, 2001) as the most likely cause of the alternating multicentury mild/moist and cold/dry periods of North-Central China. Porter and Weijian’s work thus helps establish the global extent of the Medieval Warm Period as well as its likely solar origin.

A 2009 study provides further evidence of relationships between solar controls and the Asian Monsoon. Based on carbonate percentages and ostracod abundances found in sediment cores they extracted from Hurleg Lake in the arid Qaidam Basin of the Northeast Tibetan Plateau, Zhao *et al.* (2009) developed a history of precipitation-driven changes in lake level over the past 1,700 years, which they compared with a contemporaneous history of tree-ring-derived precipitation over surrounding mountainous terrain as well as with changes in solar activity manifest in solar proxy residual $\Delta^{14}\text{C}$ data. The authors discovered “carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the last 1000 years,” with the moisture pattern in the Qaidam Basin being “in opposite relation to tree-ring-based monsoon precipitations in the surrounding mountains, suggesting that topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region.” In addition, they found cross-spectral analysis between their moisture proxies and the solar activity proxy “shows high coherence at the ~200-year periodicity which is similar to Chinese monsoon intensity records, implying the possible solar forcing of moisture oscillations in the NE Tibetan Plateau.”

Zhao *et al.*’s work provides another example of cyclical solar activity controlling the cyclical nature of precipitation variations, wherein “higher solar output corresponds to a stronger monsoon, which intensifies the uplift of air mass on the high Tibetan Plateau and strengthens the subsidence of air mass

over the Qaidam Basin,” whereas “the reverse is true during the period of lower solar output,” so that “high solar activity is correlated with dry climate in the Qaidam Basin and increased precipitation in monsoonal areas.”

At this juncture, insights from the climate modeling effort can be instructive. In their study of centennial variations of global monsoon precipitation in the last millennium, Liu *et al.* (2009) called attention to the nonlinear responses in the climate model for a 0.2% increase in external solar forcing in triggering a 0.9% change in global monsoon precipitation, or an amplification factor of 4 to 5. Liu *et al.* explained the physical relation as follows:

We argue that the effective radiative forcing-induced land-ocean thermal contrast causes an initial increase in monsoon precipitation. This initial increase is further reinforced by the increase in moisture supply because the warming induced by effective radiative heating tends to increase atmospheric moisture content. The increase in moisture supply can induce a positive feedback between the latent heat release (in precipitation) and monsoon flow convergence, thus further amplify the latent heat release, which may ultimately amplify the atmospheric circulation response. Therefore, the humidity feedback is a key amplifier linking solar irradiance and monsoon.” (p. 2368)

In a study of the North American monsoon, Asmerom *et al.* (2007) developed a high-resolution climate proxy for the southwest United States in the form of $\delta^{18}\text{O}$ variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw $\delta^{18}\text{O}$ data revealed significant peaks the researchers say “closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993).” They report cross-spectral analysis of the $\Delta^{14}\text{C}$ and $\delta^{18}\text{O}$ data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon); this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar

link to Holocene climate operates “through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean.”

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3.5.4 Streamflow

Streamflow is a climate variable related to precipitation, droughts, and floods. The studies reviewed here consider whether a significant solar influence on this variable.

Pederson *et al.* (2001) used tree-ring chronologies to reconstruct annual precipitation and streamflow histories in northeastern Mongolia over the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods revealed “variations over the recent period of instrumental data are not unusual relative to the prior record.” The authors say the reconstructions “appear to show more frequent extended wet periods in more recent decades,” but they note this observation “does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models.” The researchers also observe spectral analysis of the data revealed significant periodicities around 12 and 20–24 years, suggesting “possible evidence for solar influences in these reconstructions for northeastern Mongolia.”

In Western Europe, several researchers have studied precipitation histories of regions along the Danube River and their effects on river discharge, with some studies suggesting an anthropogenic signal present in the latter decades of the twentieth century is responsible for that period’s drier conditions. Ducic (2005) analyzed observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He found the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was nearly equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950); the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. The discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be “completely inside the limits of the whole

series” and only slightly ($38 \text{ m}^3\text{s}^{-1}$ or 0.7 percent) less than the 260-year mean of $5356 \text{ m}^3\text{s}^{-1}$. In conclusion, Ducic states “modern discharge fluctuations do not point to [a] dominant anthropogenic influence”; further analysis suggests the detected cyclicity in the record may “point to the domination of the influence of solar activity.”

Kondrashov *et al.* (2005) applied advanced spectral methods to fill in data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels on the Nile over the 1,300-year period AD 622 to 1922. They found several statistically significant periodicities, including cycles of 256, 64, 19, 12, 7, 4.2, and 2.2 years. Kondrashov *et al.* state the 4.2- and 2.2-year oscillations are likely the product of El Niño-Southern Oscillation variations, the 7-year cycle may be related to North Atlantic influences, and the longer-period oscillations may be due to solar-related forcings.

Mauas *et al.* (2008) note river streamflows “are excellent climatic indicators,” especially in the case of rivers “with continental scale basins” that “smooth out local variations” and can thus “be particularly useful to study global forcing mechanisms.” Focusing on South America’s Parana River—the world’s fifth largest in terms of drainage area and fourth largest with respect to streamflow—Mauas *et al.* analyzed streamflow data collected continuously on a daily basis since 1904. They report the detrended time series of the streamflow data were correlated with the detrended times series of both sunspot number and total solar irradiance, yielding Pearson’s correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69, respectively, at “a significance level higher than 99.99% in both cases.” This is strong evidence that solar variability, not manmade greenhouse gas emissions, was responsible for variation in Parana River streamflow during the modern industrial era.

A follow-up study by Mauas *et al.* (2011) analyzed river streamflows during the Little Ice Age. The authors write low water levels and low level in the flow of the Pirana River (and others) were found during a time of “unusual” minimum of solar activity, once again affirming the notion that solar activity induces significant variations in streamflow.

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3.6 Future Influences

Sunspot activity for Cycle 23 (from May 1996 until about 2008–2009) and the relatively slow and muted rising phase of Cycle 24 are unusual. This has heightened interest not only in solar magnetic field data but also more generally in the nature of the solar-climate connection. In concluding this chapter we examine recent research and scientists’ thoughts on the potential influence of the Sun on Earth’s future climate.

Livingston and Penn (2009) confirm “something is unusual about the current sunspot cycle,” specifically “the current solar minimum has been unusually long.” They note “with more than 670 days without sunspots through June 2009, the number of spotless days has not been equaled since 1933.” In addition, they note, “the solar wind is reported to be in a uniquely low energy state since space measurements began nearly 40 years ago,” citing the work of Fisk and Zhao (2009).

In 2006, Livingston and Penn reported the magnetic field strengths of sunspots “were decreasing with time, independent of the sunspot cycle” and “a simple linear extrapolation of those data suggested that sunspots might completely vanish by 2015.” With several years’ more data in hand, they report in 2009 “the predicted cycle-independent dearth in sunspot numbers has proven accurate,” with sunspots still on track potentially to disappear in four to five years. That possibility led the two researchers to wonder openly whether their findings represent “an

omen of long-term sunspot decline, analogous to the Maunder Minimum,” the period 1645–1715 “when through several 11-year periods the Sun displayed few if any sunspots.” They note “models of the Sun’s irradiance suggest that the solar energy input to the Earth decreased during that time and that this change in solar activity could explain the low temperatures recorded in Europe during the Little Ice Age (Lean *et al.*, 1992).”

The decline of the umbral magnetic field strength noted by Livingston and Penn and shown in Figure 3.6.1 (from Livingston *et al.* 2012, based on measurements for the near-infrared feature at Fe I 1565 nm) is not universally recognized. Pevtsov *et al.* (2011) found the sunspot field strengths (based on measurements for the visible line feature at Fe I 630 nm) tend to rise and wane with solar activity cycle; they do not detect a long-term decline of magnetic field strength. Rezaei *et al.* (2012), using more limited observations of 183 sunspots from the Tenerife Infrared Polarimeter, tend to support Pevtsov *et al.*

Nagovitsyn *et al.* (2012) offered a working explanation of the discrepancies between different observations and interpretations, noting opposing trends and dynamics in the largest and smallest sunspots. They write, “Suppose that during a grand solar minimum (e.g., Maunder minimum) the sunspots do not vanish all together, but only the large sunspots disappear. This change would not require the complete shutdown of the solar dynamo. Only the depth dependence of the dynamo will change, and it would favor the production of small sunspots.” They point out “the smallest sunspots are much harder to detect, especially with the visual observations conducted with relatively poor telescopes, which could explain the low sunspot counts during some of the past grand minima.”

Nagovitsyn *et al.* also point out, “modern observations suggest that the smaller sunspots are less likely to be associated with flare and coronal mass ejection activity, and thus, the magnetic fields on smaller scales may have a reduced effect on the amount of the magnetic field expelled to the heliosphere. The latter may affect the secondary proxies of the solar activity (e.g., cosmic-ray flux and frequency of aurorae) that are often used as additional identifiers of the Maunder minimum.” They conclude, “this possibility that the grand minima in solar activity can be related to changes in size of sunspots produced by the dynamo should be explored further ...”

Obridko *et al.* (2012) discussed the unusual

sunspot minimum for Cycle 23 and what might be expected for the next several decades. They conclude, “after the high cycles of the twentieth century, the solar activity now turns to an average level [for Cycle 24] (rather than to a low one, as some authors believe), and only by the latter half of [the] twenty-first century we can wait for a great minimum of Dalton’s type [i.e., 1790–1820]. The probability of a Maunder’s type minimum [i.e., 1645–1715] is minimal.”

The direct observations as updated in Livingston *et al.* (2012), however, do not rule out a highly muted future sunspot activity cycle. “By extrapolating our sunspot formation fraction to the predicted peak of Cycle 24 (in mid-2013) the sunspot formation fraction would be approaching 0.5 [i.e., a peak in the smoothed sunspot number of about 66–87 as estimated in Penn and Livingston 2011],” they write. “This suggests a rather small SSN for this cycle, in agreement with some recent Cycle 24 predictions.”

Projecting further into the future, Livingston *et al.* note, “And while there is no physical mechanism which suggests that we should extrapolate further, it is fascinating to see that the sunspot formation fraction would be below 0.2 [i.e., a peak in the smoothed sunspot number of about 7–20 for Cycle 25 as estimated in Penn and Livingston 2011] by 2020. This would suggest that although magnetic flux would be erupting at solar surface during Cycle 25, only a small fraction of it would be strong enough to form visible sunspots or pores,” as shown in Figure 3.6.2. “Such behavior would be highly unusual,” they note, “since such a small solar maximum has not been observed since the Maunder Minimum.”

In addition to the direct approach of studying the Sun itself, other researchers study the decadal, multidecadal, centennial, bicentennial, and even millennial periods in available climate and solar records in order to extrapolate solar activity into the future.

Solheim *et al.* (2012) point out Archibald (2008) was the first to recognize previous sunspot cycle length (PSCL) has a predictive power for temperature in the next sunspot cycle, if the raw (unsmoothed) value for the sunspot cycle length (SCL) is used, which Archibald demonstrated with data from de Bilt in the Netherlands; Hanover, New Hampshire, USA; Portland, Maine, USA; Providence, Rhode Island, USA; and Archangel, Russia.

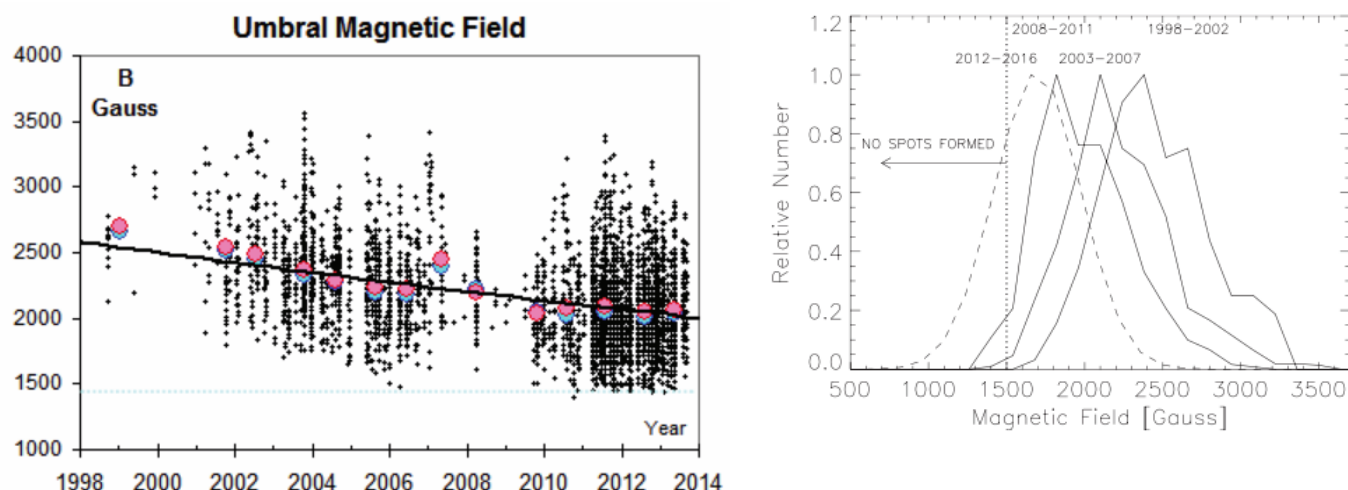


Figure 3.6.1. The measured sunspot umbral magnetic field strength from 1998 until April 2013 (left panel) and the distribution of the magnetic field strength for the same interval and the predicted distribution for 2012-2016 (right panel). It is predicted that a significant fraction of the magnetic fields will be below the threshold of 1500 G for the formation of sunspot. Adapted from Livingston, W., Penn, M.J., and Svalsgaard, L. 2012. Decreasing sunspot magnetic fields explain unique 10.7 cm radio flux. *The Astrophysical Journal Letters* **757**: L8. Left panel updated by Livingston in private correspondence, September 9, 2013.

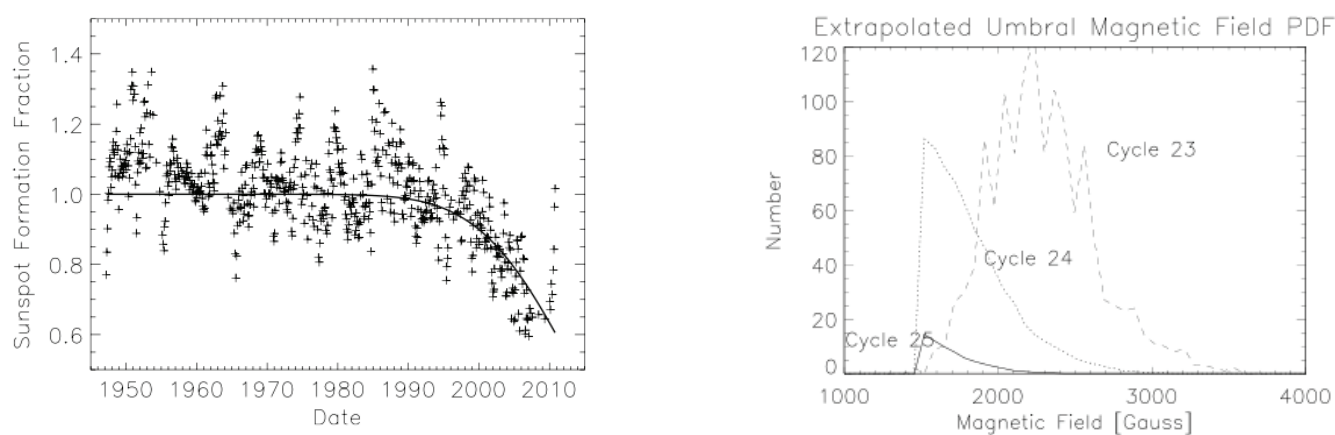


Figure 3.6.2. The history of the fraction of sunspot formation from about 1947 to present (left panel) illustrating the unusual nature of Cycles 23 and 24. The estimated distribution of sunspot magnetic field strengths for Cycle 23 contrasting those extrapolated for Cycles 24 and 25 (right panel). Left panel also adapted from Livingston *et al.* (2012). Right panel adapted from Penn, M.J. and Livingston, W. 2011. Long-term evolution of sunspot magnetic fields. In Choudhary, D.P. and Strassmeier, K.G. (Eds.) IAU Symposium No. 273, *The Physics of Sun and Star Spots*, (Cambridge: Cambridge University Press), pp. 126–133.

Solheim *et al.* further explored this relationship by comparing the raw SCL values and temperatures in the same and next sunspot cycles for a selection of weather stations in Norway and other European locations as well as sites across the North Atlantic

region, including Armagh, Archangel, the Faroe Islands, Iceland, Svalbard and Greenland. The stations offered long weather records at places with small populations (to minimize urban heat island effects) in both coastal and inland locations.

The three Norwegian researchers found significant linear relationships between the average air temperature in a solar cycle and the length of the previous solar cycle for 12 of 13 weather stations in Norway and in the North Atlantic, as well as for 60 European stations and for the HadCRUT3N database. For Norway and the other European stations, they found “the solar contribution to the temperature variations in the period investigated is of the order 40%,” while “an even higher contribution (63–72%) is found for stations at the Faroe Islands, Iceland and Svalbard,” which they note is considerably “higher than the 7% attributed to the Sun for the global temperature rise in AR4 (IPCC, 2007).”

Solheim *et al.* say their findings imply “an annual average temperature drop of 0.9°C in the Northern Hemisphere during solar cycle 24,” and “for the measuring stations south of 75°N, the temperature decline is of the order 1.0–1.8°C and may already have started.” For Svalbard, they say “a temperature decline of 3.5°C is forecasted in solar cycle 24 for the yearly average temperature,” and “an even higher temperature drop is forecasted in the winter months (Solheim *et al.*, 2011).” They caution, “since solar forcing on climate is present on many timescales, we do not claim that our result gives a complete picture of the Sun’s forcing on our planet’s climate.”

Ludecke *et al.* (2013) considered six periodic components with timescales greater than 30 years in the composite of a six-station temperature record from Central Europe since about 1757 AD, creating a very good reconstruction of the original instrumental records. They project a substantial cooling of the Central European temperature in the next one to two decades but caution their result “does not rule out a warming by anthropogenic influences such as an increase of atmospheric CO₂.” The authors also note, “while ... many indications point to the oscillations as intrinsic dynamics of the Earth, external causes for periodic dynamics cannot be ruled out.”

The weak and delayed Cycle 24 surprised a number of solar experts, but not all of them. In 2003, a small group led by Mark Clilverd of the British Antarctic Survey in Cambridge had sensed something was amiss even before there were signs pointing to a slowdown in the Schwabe solar cycles (Clilverd *et al.*, 2003). Clilverd *et al.* produced a solar activity forecast through 2140, which they further refined in 2006 (Clilverd *et al.*, 2006). They predicted a strongly reduced Cycle 24 would mark the start of a solar activity slumber extending until the year 2030, at which time solar activity would pick up and remain at

a more elevated level until 2100, after which another pronounced, extended quiet period would ensue. Their forecast was based on a careful analysis of the entire suite of known solar cycles, from the 11-year Schwabe Cycle to the 2,300-year Hallstatt Cycle. By extending these oscillations into the future, they correctly predicted the collapse in solar activity in Cycle 24 that followed a few years later.

In analyzing the global temperature data records (HadCRUT3 and HadCRUT4, respectively) directly, Loehle and Scafetta (2011) and Tung and Zhou (2013) conclude a large fraction of recent observed warming (60 percent over 1970–2000 and 40 percent over the past 50 years) can be accounted for by the natural upswing of the 60-year climatic cycle during its warming phase. Loehle and Scafetta (2011) proffer that “a 21st Century forecast suggests that climate may remain approximately steady until 2030–2040, and may at most warm 0.5–1.0°C by 2100 at the estimated 0.66°C/century anthropogenic warming rate, which is about 3.5 times smaller than the average 2.3°C/century anthropogenic warming rate projected by the IPCC up to the first decades of the 21st century. However, additional multisecular natural cycles may cool the climate further.”

In an independent analysis of global temperature data from the Climatic Research Unit at the University of East Anglia and the Berkeley Earth Surface Temperature consortium, Courtillot *et al.* (2013) arrive at a new view of the significance of the ~60 yr oscillation. They interpret the 60-year period found in the global surface temperature records as “a series of ~30-yr long linear segments, with slope breaks (singularities) in ~1904, ~1940, and ~1974 (± 3 yr), and a possible recent occurrence at the turn of the 21st century.” Courtillot and his colleagues suggest “no further temperature increase, a dominantly negative PDO index and a decreasing AMO index might be expected for the next decade or two.”

By extrapolating present solar cycle patterns into the future, several scientists have suggested a planetary cooling may be expected over the next few decades. The Gleissberg and Suess/de Vries cycles will reach their low points between 2020 and 2040 at a level comparable to what was experienced during the Dalton Minimum. At that time, around 1790–1820, global temperatures were nearly 1°C lower than they are today; conservatively, at least half of that cooling was due to a weaker Sun.

Moreover, the Pacific Decadal Oscillation (PDO) is expected to be in a cool phase by 2035, and the Atlantic Multidecadal Oscillation (AMO) will begin

to drop around 2020. Such internal climate cycles are generally responsible for about 0.2 to 0.3°C of the temperature dynamic.

By calibrating the natural climate cycles to the documented geological data series of the past, we can project a total cooling contribution from these natural climate forcings of 0.4 to 0.6°C by the year 2035 as compared to today. Such cooling might be masked to some extent by anthropogenic effects, such as greenhouse gases, urbanization, and land-use change. Only time will tell whether such interpolations of future climate are correct, but given the stagnant temperatures experienced over the past decade, the odds may favor the Sun.

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4

Observations: Temperature Records

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Key Findings

Introduction

4.1 Global Temperature Records

- 4.1.1 Cause of Late Twentieth Century Warming
- 4.1.2 Urbanization Taints Modern Records
- 4.1.3 Potential Problems with Climate Proxies

4.2 The Non-Uniqueness of Current Temperatures

- 4.2.1 The Warmth of Prior Interglacial Climates
- 4.2.2 A Global Medieval Warm Period
- 4.2.3 Prior Warm Periods in Northern Hemisphere
- 4.2.4 Regional Manifestations

4.3 Predicted vs. Observed Global Warming Effects on ENSO

- 4.3.1 Frequency and Intensity
- 4.3.2 Influence on Extreme Weather Events

Key Findings

The following bulleted points summarize the main findings of this chapter:

- The Intergovernmental Panel on Climate Change (IPCC) contends the warming of the past half-century is unprecedented in the past millennium and anthropogenic in origin. In contrast, based upon the evidence presented here and in other chapters of this volume, the Nongovernmental International Panel on Climate Change (NIPCC) concludes natural variability is responsible for late twentieth century warming and the cessation of warming since 1998. The modern rise of carbon dioxide and other atmospheric greenhouse gases has had little, if any, measurable effect on twentieth century climate.
- Filtering out urbanization and related land-use effects in the temperature record is a complicated task, and there is solid evidence the methods currently used are inadequate. Urbanization may account for a larger portion of the modern temperature rise than the IPCC acknowledges.
- Surface-based temperature histories of the globe almost certainly contain a significant warming bias introduced by insufficient corrections for the non-greenhouse-gas-induced urban heat island effect. It may be next to impossible to make proper corrections for this deficiency, as the urban heat island of even small towns dwarfs any concomitant augmented greenhouse effect that may be present.
- The IPCC claim of robust evidence of amplified CO₂-induced warming in Earth's polar regions is patently false, having been invalidated time and again by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies in Earth's polar regions demonstrate the atmosphere's CO₂ concentration

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is not a major player in bringing about significant changes in Earth's climate.

- Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration, revealing the true inability of carbon dioxide to drive climate change throughout the Holocene. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades and centuries even though the atmosphere's CO₂ concentration remained approximately 30 percent lower than it is today.
- The IPCC concludes "there is high confidence that the Medieval Climate Anomaly was not characterized by a pattern of higher temperatures that were consistent across seasons and regions" (p. 5-4 of the Second Order Draft of AR5, dated October 5, 2012). Quite to the contrary, an enormous body of literature clearly demonstrates the IPCC's assessment of the Medieval Climate Anomaly (MCA) is incorrect. The degree of warming and climatic influence during the MCA indeed varied from region to region, and hence its consequences were manifested in a variety of ways. But literally hundreds of peer-reviewed scientific articles confirm it occurred and was a global phenomenon.
- 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. Observational data do not agree with the models' claims: In nearly all historical records, 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).

Introduction

In its current and prior assessment reports the IPCC makes clear its position that the past few decades were the warmest of the past hundred years on the planet, and possibly of the entire past millennium. Their statements on this topic include:

Starting in the 1980s each decade has been significantly warmer than all preceding decades. ... All ten of the warmest years have occurred since 1997, with 2010 and 2005 effectively tied for the warmest year on record (Second Order Draft of AR5, dated October 5, 2012, p. 2-33).

Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years (Summary for Policy Makers, Fourth Assessment Report, p. 9).

Better understanding of pre-instrumental data shows that warming since the mid-20th century is far outside the range of internal climate variability estimated from such records (Second Order Draft of AR5, dated October 5, 2012, p. 10-3).

The IPCC further asserts the supposedly unprecedented high air temperatures of the present are largely the consequence of increasing anthropogenic CO₂ emissions resulting from the burning of fossil fuels, claiming:

It is *very unlikely* that reconstructed temperatures since 1400 can be explained by natural internal variability alone. Climate model simulations that include only natural forcings can explain a substantial part of the pre-industrial inter-decadal temperature variability since 1400 on hemispheric scales. However such simulations fail to explain more recent warming since 1950 without the inclusion of anthropogenic increases in greenhouse gas concentrations. The warming since 1950 is far outside the range of similar length trends estimated in residual internal variability estimated from reconstructions of the past millennium (Second Order Draft of AR5, dated October 5, 2012, p. 10-5).

We conclude it is *extremely likely* that human activities have caused most of (at least 50%) the observed increase in global average temperatures since the 1950s and that it is *virtually certain* that this warming is not due to internal variability alone (Second Order Draft of AR5, dated October 5, 2012, p. 10-3)

These two most basic assertions of the IPCC—that the warming of the past half century is unprecedented in the past millennium and anthropogenic in origin—serve as the foundation of nearly all of the work conducted by the IPCC. These assertions are the basic building blocks upon which

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politicians and governments have sought to radically reformulate the energy basis of the industrialized world to avoid a host of climatic consequences they insist will occur (or are occurring) as temperatures continue to rise.

The present chapter examines these two temperature-related claims and finds the IPCC's assertions are based on a limited and narrow interpretation of the available scientific literature. Many published studies, for example, question the accuracy of the surface temperature record, collectively demonstrating the datasets upheld by the IPCC likely overestimate the warming that has occurred over the past half-century. In addition, the publication of many historical paleoclimate records reveal there is nothing unusual, unnatural, or unprecedented about the current level of planetary warmth. These facts, coupled with the problems inherent in climate models (Chapter 1 of this volume), the failure of the models to properly account for and incorporate important forcings and feedbacks into their model runs (Chapters 2 and 3), and the array of real-world observations that run counter to the model projections with respect to various climate and other related phenomena (this chapter and Chapters 5, 6, and 7), all demonstrate the IPCC is premature—if not flat-out wrong—in attributing recent warming to anthropogenic CO₂ emissions.

4.1 Global Temperature Records

4.1.1 Discerning the Cause of Late Twentieth Century Global Warming

The IPCC has concluded it is “*extremely likely*” the anthropogenic release of greenhouse gases into the atmosphere has caused most of the increase in global average temperature they claim has been observed since the 1950s.

In brief, the reason for the IPCC's confidence stems from comparisons of global climate model runs of the twentieth century using natural forcings and natural *plus* anthropogenic forcings. When the models are run throughout the twentieth century using natural forcings alone, they are unable to reproduce the rise seen in various global temperature datasets. When they are run with the added anthropogenic forcing due to CO₂ and other greenhouse gases, there is relatively good agreement between the model projections and temperature observations. Thus, the IPCC attributes the mid- to late-twentieth century observational warming to rising greenhouse gases.

In making this attribution, however, the IPCC makes several assumptions. First, it assumes the magnitude of the mid- to late-twentieth century rise in temperature, as presented in the global land and ocean datasets, is robust. (It is not; see Section 4.1.2.) Second, the IPCC assumes the models are using an accurate temperature sensitivity to represent the modern rise in greenhouse gases. (They are not; see Chapter 1.1.5.) Third, the IPCC assumes the models correctly capture and portray each of the important processes that affect climate. (They do not; see Chapters 1, 2, and 3.) Fourth, the IPCC assumes the models correctly depict and account for natural variability. (They do not, as evidenced by material presented in all chapters of this volume.)

With respect to the first assumption, a number of difficulties are encountered in obtaining accurate global temperature measurements and assembling them into aggregate histories of global climate change over the era of modern instrumentation. These difficulties, if not properly addressed, can induce significant errors into the global temperature record. The magnitude of these errors in many instances has been reported to be as large as or larger than the anthropogenic signal anticipated by the IPCC to be residing in such datasets.

Among such potential errors are temporal changes in microclimate surrounding temperature measurement sites, such as urbanization, which often go unrecognized or for which insufficient adjustments are made; long-term degradation of the shelters that house the temperature-measuring equipment, such as the shelters' white paint becoming less reflective and their louvers partially obstructed; changes in what is actually being measured, such as true daily maximum and minimum temperatures or temperatures at specified times of day; changes in measurement devices and ways of accessing the data, such as changing from having to open the shelter door to read the temperature, as was done in earlier days, to not having to do so, due to the automatic recording of the data, as has become commonplace in more recent times; general station degradation and many station closures over time; the changing and uneven geographical representation of the surface temperature network; poor attention to careful acquisition of data in many parts of the world; and numerous problems associated with obtaining a correct and geographically complete record of surface air temperature over the 70 percent of the globe that is covered by oceans.

Arguably the most serious of the potential

inaccuracies is that related to urbanization, addressed in more detail in Section 4.1.2. As demonstrated there, the impact of population growth on the urban heat island effect is very real and can be very large, vastly overshadowing the effects of natural temperature change. Towns with as few as a thousand inhabitants, for example, typically create a warming of the air within them that is more than twice as great as the increase in mean global air temperature presumed to have occurred since the end of the Little Ice Age. Urban heat islands of the great metropolises of the world are much larger, creating warmings that rival those that occur between full-fledged ice ages and interglacials. Given the potential of this phenomenon to introduce errors of such magnitude into the temperature records of the past century, it is surprising the IPCC is mostly dismissive of this topic and its significance in its *Fifth Assessment Report*.

Other observations also point to problems with the global surface air temperature record. The satellite microwave-sounding-unit temperature record shows less warming when compared with surface temperature records since coming online in 1979, and the weather-balloon temperature record also shows less warming than the surface temperature records since the 1940s.

The second major assumption made by the IPCC in attributing the late twentieth century rise in temperature to the modern rise in atmospheric greenhouse gases pertains to climate sensitivity. Most models use a climate sensitivity in which global temperatures rise between 1.5 and 4.5°C in response to a doubling of the atmosphere's CO₂ concentration. However, as discussed in Chapter 1.1.5, these values could be as much as a factor of ten too high compared to what actually occurs in nature.

A simple test demonstrating the IPCC's faulty assessment of climate sensitivity was performed a little over a decade ago by Stanhill (2001), who examined the relationship between temperature and CO₂ over the prior 140 years. In describing the character of the global surface temperature record over this period, he said it can be broken into four parts, beginning with "a long and very irregular but generally cool first period between 1860 and 1910, followed by a very rapid, regular and prolonged period of global warming between 1910 and 1943, succeeded by an equally long period of small and irregular cooling from 1943 to 1975 and, since then, the current warming period," which latter warming stopped about the time of Stanhill's writing, revealing no statistical trend in the temperature data since 1998.

During the prolonged period of global warming in the early part of the past century, Stanhill notes, "the rate of anthropogenic releases of radiatively active gasses, the presumed cause of the current global warming, was approximately one tenth of that in the present warming period," the temperature increase of which "has been shorter, more irregular and less rapid than the earlier warming." The order-of-magnitude-greater release of greenhouse gases since 1975 has not produced a warming as dramatic as the one that occurred in the early part of the century that was coeval with the release of but one-tenth as much CO₂ and other greenhouse gases. There is thus little reason to put much credence in the IPCC's estimates on climate sensitivity. This point is further driven home in Chapter 1.1.1, where several additional examples from the peer-reviewed literature are cited to show climate is relatively insensitive to changes in CO₂, and CO₂ is a *follower* of temperature change as opposed to an *initiator* of it.

The third major assumption the IPCC makes in attributing the late twentieth century rise in temperature to the modern rise in atmospheric greenhouse gases is that the models correctly capture and portray each of the important processes that affect climate. Chapter 1 of this volume presents an in-depth discussion of the inner workings and limitations of climate models.

Climate models are important tools used to advance our understanding of current and past climate. They provide qualitative and quantitative information about potential future climate. But in spite of their sophistication, they remain only *models*. They represent simulations of the real world, constrained by their ability to correctly capture and portray each of the important processes that operate to affect climate. Chapter 1 demonstrates the models remain deficient in many aspects of their portrayal of the climate, which reduces their ability to provide reliable simulations of the future.

Confidence in a model is further based on the careful evaluation of its performance. Just because one, two, or several models agree on a particular outcome, such agreement is not sufficient grounds to conclude the model projections are robust, for the model projections must be validated against real-world observations at the appropriate temporal and spatial scales. Without such a comparison, the true performance of a model cannot be verified.

A large portion of this volume, therefore, is devoted to the evaluation of climate model projections against real-world climate and other

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biospheric data, including material from this chapter. That evaluation, summarized in the findings of numerous peer-reviewed scientific papers, reveals the models consistently fail to accurately simulate important components of the Earth-atmosphere-ocean system.

Climate models predict a unique anthropogenic “fingerprint” of CO₂-induced global warming in which there is a warming trend in the tropical troposphere that increases with altitude (see Figure 4.1.1.1.) The models further suggest climate changes due to solar variability or other known natural factors do not yield this pattern, whereas sustained greenhouse warming does.

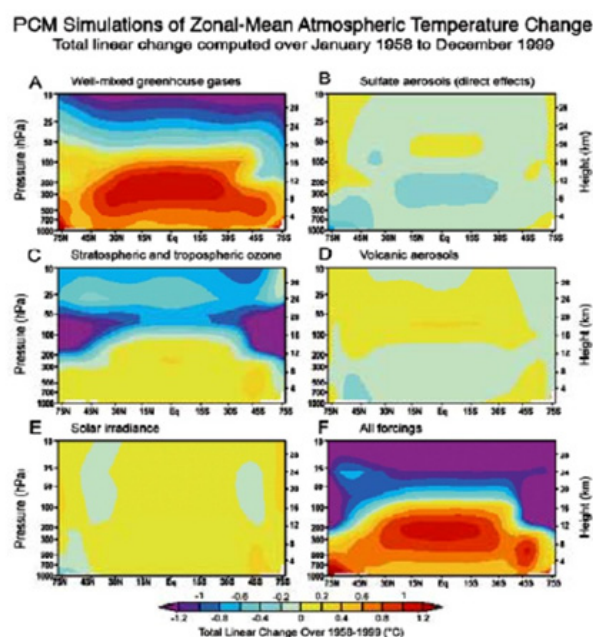


Figure 1.3. PCM simulations of the vertical profile of temperature change due to various forcings, and the effect due to all forcings taken together (after Santer *et al.*, 2000).

Figure 4.1.1.1. Model-calculated zonal mean atmospheric temperature change from 1890 to 1999 (degrees C per century) as simulated by climate models from [A] well-mixed greenhouse gases, [B] sulfate aerosols (direct effects only), [C] stratospheric and tropospheric ozone, [D] volcanic aerosols, [E] solar irradiance, and [F] all forcings (U.S. Climate Change Science Program 2006, p. 22). Note the pronounced increase in warming trend with altitude in figures A and F, which the IPCC identified as the ‘fingerprint’ of greenhouse forcing.

The comparison of these projections with observations was first attempted in the IPCC’s *Second Assessment Report* (SAR) (IPCC-SAR, 1996, p. 411).

Its Chapter 8, titled “Detection and Attribution,” attributed observed temperature changes to anthropogenic factors: greenhouse gases and aerosols. The attempted match of warming trends with altitude turned out to be spurious, since it depended entirely on a particular choice of time interval for the comparison (Michaels and Knappenberger, 1996). Similarly, an attempt to correlate the observed and calculated geographic distribution of surface temperature trends (Santer *et al.* 1996) involved making changes on a published graph that could and did mislead readers (Singer, 1999, p. 9; Singer, 2000, pp. 15, 43–44). In spite of these shortcomings, IPCC-SAR concluded the data matched the observations and “the balance of evidence” therefore supported anthropogenic global warming.

With the availability of higher-quality temperature data, especially from balloons and satellites, and with improved models, it has become possible to make this comparison in a more realistic way. This was done in a report issued by the U.S. Climate Change Science Program (CCSP) in April 2006, making it readily available to the IPCC for its *Fourth Assessment Report*. It permits a more realistic comparison of the data (Karl *et al.*, 2006).

The CCSP report is an outgrowth of a National Academy of Sciences (NAS) report, “Reconciling Observations of Global Temperature Change,” issued in January 2000 (NAS, 2000). The NAS report compared surface and troposphere temperature trends and concluded they cannot be reconciled. Six years later, the CCSP report expanded considerably on the NAS study. It was essentially a specialized report addressing the most crucial issue in the global warming debate: Is current global warming anthropogenic or natural? The CCSP findings were unequivocal. Although all greenhouse models show an increasing warming trend with altitude, peaking around 10 km at roughly two times the surface value, the temperature data from balloons give the opposite result: no increasing warming, but rather a slight cooling with altitude in the tropical zone. See Figures 4.1.1.2 and 4.1.1.3, reproduced directly from the CCSP report.

The CCSP executive summary inexplicably claims agreement between observed and calculated patterns, the opposite of what the report itself documents. It tries to dismiss the obvious disagreement shown in the body of the report by suggesting there might be something wrong with balloon and satellite data instead of the model projections. Unfortunately, many people do not read

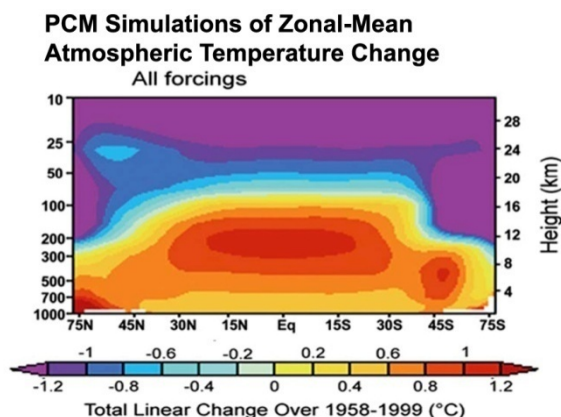


Figure 4.1.1.2. Greenhouse-model-predicted temperature trends versus latitude and altitude; this is figure 1.3F from CCSP 2006, p. 25. Note the increased temperature trends in the tropical mid-troposphere, in agreement also with the IPCC result (IPCC-AR4 2007, p. 675).

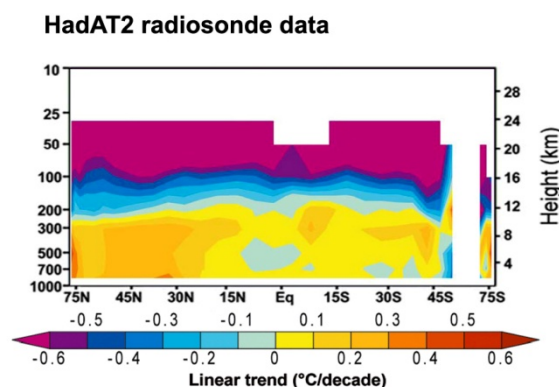


Figure 4.1.1.3. By contrast, observed temperature trends versus latitude and altitude; this is figure 5.7E from CCSP 2006, p. 116. These trends are based on the analysis of radiosonde data by the Hadley Centre and are in good agreement with the corresponding U.S. analyses. Notice the absence of increased temperature trends in the tropical mid-troposphere.

beyond the summary and have therefore been misled to believe the CCSP report supports anthropogenic warming. It does not.

The same information also can be expressed by plotting the difference between surface trend and troposphere trend for the models and for the data (Singer, 2001). As seen in Figure 4.1.1.4a and 4.1.1.4b, the models show a histogram of negative values (i.e., surface trend less than troposphere trend) indicating atmospheric warming will be greater than surface warming. By contrast, the data show mainly positive values for the difference in trends, demon-

Modeled and Observed Temperature Trends in the Tropics (20°S - 20°N)

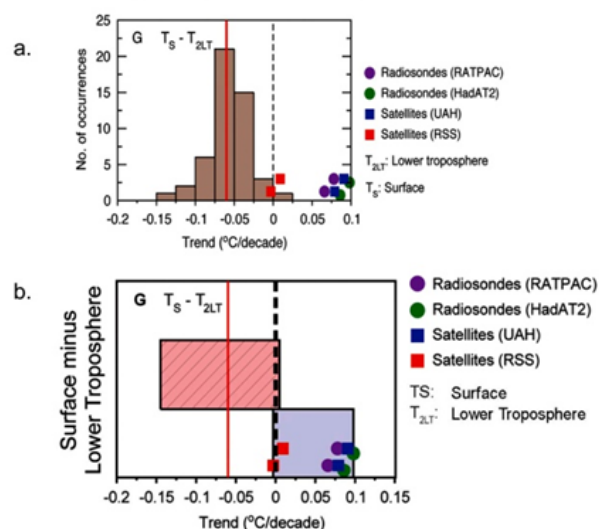


Figure 4.1.1.4a. Another way of presenting the difference between temperature trends of surface and lower troposphere; this is figure 5.4G from CCSP 2006, p. 111. The model results show a spread of values (histogram); the data points show balloon and satellite trend values. Note that the model results hardly overlap with the actual observed trends. (The apparent deviation of the RSS analysis of the satellite data is as yet unexplained.)

Figure 4.1.1.4b. By contrast, the executive summary of the CCSP report presents the same information as Figure 4.2.1.4a in terms of “range” and shows a slight overlap between modeled and observed temperature trends (Figure 4G, p. 13). However, the use of “range” is clearly inappropriate (Douglass et al. 2007) because it gives undue weight to outliers.

strating measured warming is occurring principally on the surface and not in the atmosphere.

The same information can be expressed in yet a different way, as seen in research papers by Douglass *et al.* (2004, 2007), as shown in Figure 4.1.1.5. The models show an increase in temperature trend with altitude, but the observations show the opposite.

This mismatch of observed and modeled warming of the tropical troposphere has been upheld most recently by Singer (2013), and this incongruity between model projection and data observations clearly falsifies the model output. The IPCC seems to be aware of this contrary evidence but has tried to ignore it or wish it away. The summary for policymakers of IPCC’s *Fourth Assessment Report* (IPCC 2007-I, p. 5) distorts the key result of the

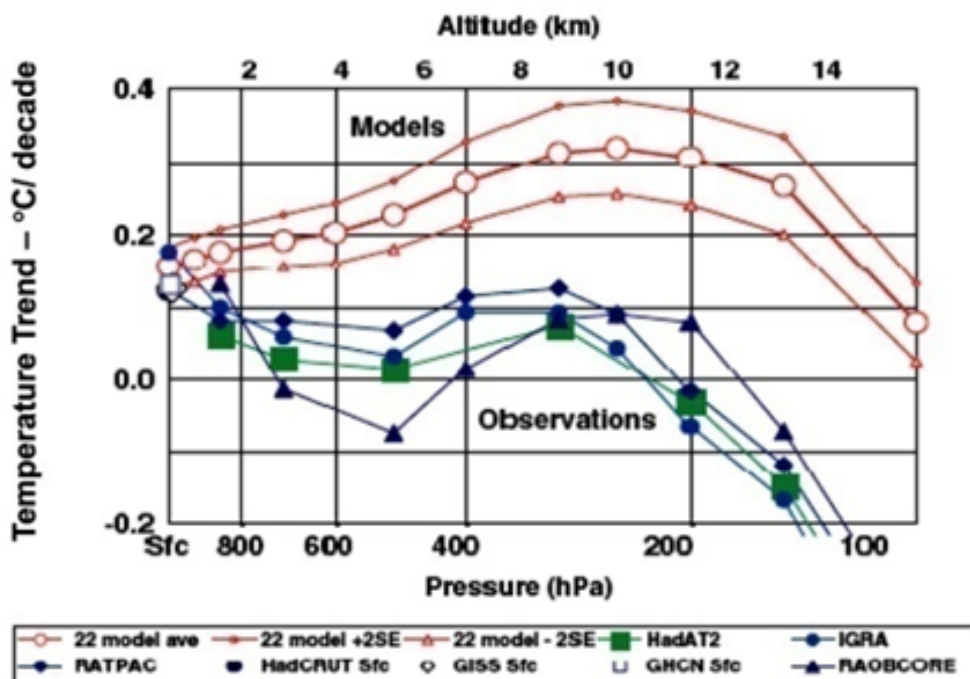
Models and Observations Disagree [Douglass, Christy, Pearson, Singer 2007]

Figure 4.1.1.5. A more detailed view of the disparity of temperature trends is given in this plot of trends (in degrees C/decade) versus altitude in the tropics. Models show an increase in the warming trend with altitude, but balloon and satellite observations do not. Adapted from Douglass, D.H., Christy, J.R., Pearson, B.D., and Singer, S.F. 2007. A comparison of tropical temperature trends with model predictions. *International Journal of Climatology* (Royal Meteorological Society). DOI:10.1002/joc.1651.

CCSP report: “New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record, and are consistent within their respective uncertainties, largely reconciling a discrepancy noted in the TAR.” How is this possible? It is done partly by using the concept of “range” instead of the statistical distribution shown in Figure 4.1.1.4a. But “range” is not a robust statistical measure because it gives undue weight to “outlier” results. If robust probability distributions were used, they would show an exceedingly low probability of any overlap of the modeled and observed temperature trends.

If one takes greenhouse model results seriously, the greenhouse fingerprint would suggest the true surface trend should be only 30 to 50 percent of the observed balloon/satellite trends in the troposphere. In that case, one would end up with a much-reduced surface warming trend, an insignificant anthropogenic

effect, and a minor greenhouse-induced warming in the future.

While discussing other important failures in model performance, Spencer (2013) also highlights this model vs. observation discrepancy of temperatures in the tropical troposphere. In written testimony before the U.S. Senate Environment and Public Works Committee, he notes “the only truly global temperature measurements, unaffected by artifacts such as urban heat island effects, are for the bulk atmosphere from Earth-orbiting satellites,” adding, “all other measurements are at points and so are geographically incomplete.”

The composite satellite record of temperature anomalies of the lower troposphere is presented in Figure 4.1.1.6. Spencer discusses several significant features elucidated by this record:

1. The magnitude of global-average atmospheric warming between 1979 and 2012 is only about

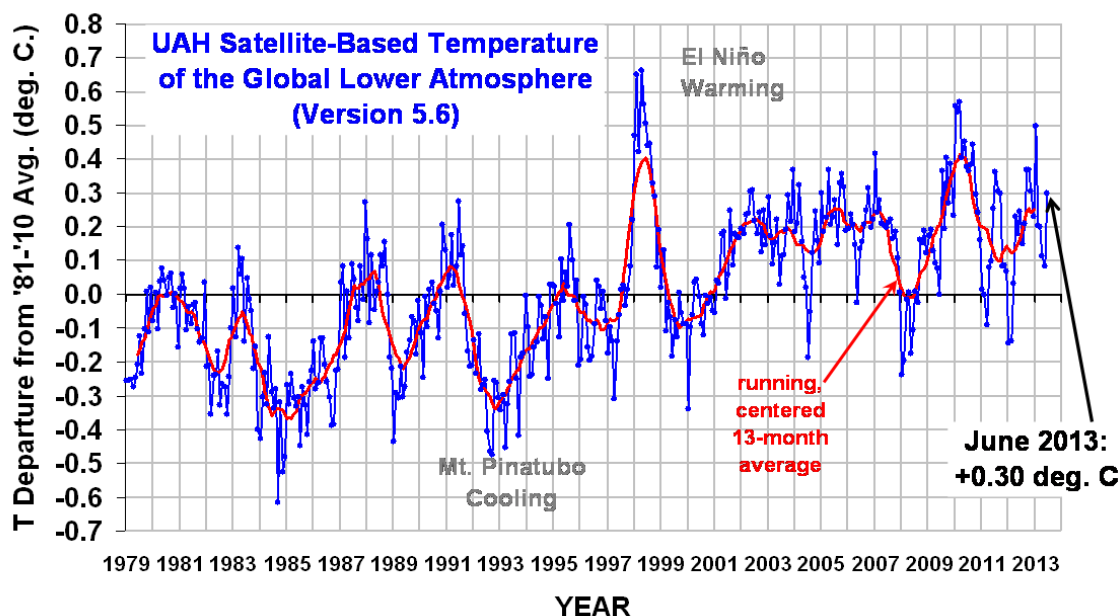


Figure 4.1.1.6. UAH global lower tropospheric (LT) temperature variations between January 1979 and June 2013. Adapted from Spencer, R.W. 2013. Statement to the U.S. Senate Environment and Public Works Committee, 19 July 2013, Washington, DC.

50% that predicted by the climate models relied upon by the IPCC in their projections of global warming.

2. The level of warming in the most recent 15 year period is not significantly different from zero, despite this being the period of greatest greenhouse gas concentration. This is in stark contrast to claims that warming is “accelerating.”
3. The level of observed tropical atmospheric warming since 1979 is dramatically different from that predicted by climate models; it is below the projections of all 73 models we have analyzed (see Figure 4.1.1.7).

With respect to his third point, Spencer provides a graph of mid-tropospheric temperature variations for the tropics (20°N to 20°S) in 73 current (CMIP5) climate models versus measurements made from two satellite and four weather balloon datasets. His graph is reproduced here as Figure 4.1.1.7.

The level of disagreement between the models and observations of tropical mid-tropospheric temperatures in Figure 4.1.1.7 is striking. It reveals, for example, the models’ projected average values are 0.5°C higher than observations at the end of the

record. Although these data are restricted to the tropics (from 20°N to 20°S), Spencer notes “this is where almost 50% of the solar energy absorbed by the Earth enters the climate system.”

Comparing the models’ output with observational data, Spencer notes the difference is “related to the lack of a middle- and upper-tropospheric ‘hotspot’ in the observations, which the models produce in response to surface warming combined with positive water vapor feedback,” leading him to state, “the observations might be telling us that the global warming response to increasing CO₂ (and any natural warming influence) is not being amplified by water vapor.”

Spencer candidly concludes:

It is time for scientists to entertain the possibility that there is something wrong with the assumptions built into their climate models. *The fact that all of the models have been peer reviewed does not mean that any of them have been deemed to have any skill for predicting future temperatures.* In the parlance of the Daubert standard for rules of scientific evidence, the models have not been successfully *field tested* for predicting climate change, and so far their *error rate* should preclude their use for predicting future climate change (Harlow & Spencer, 2011).

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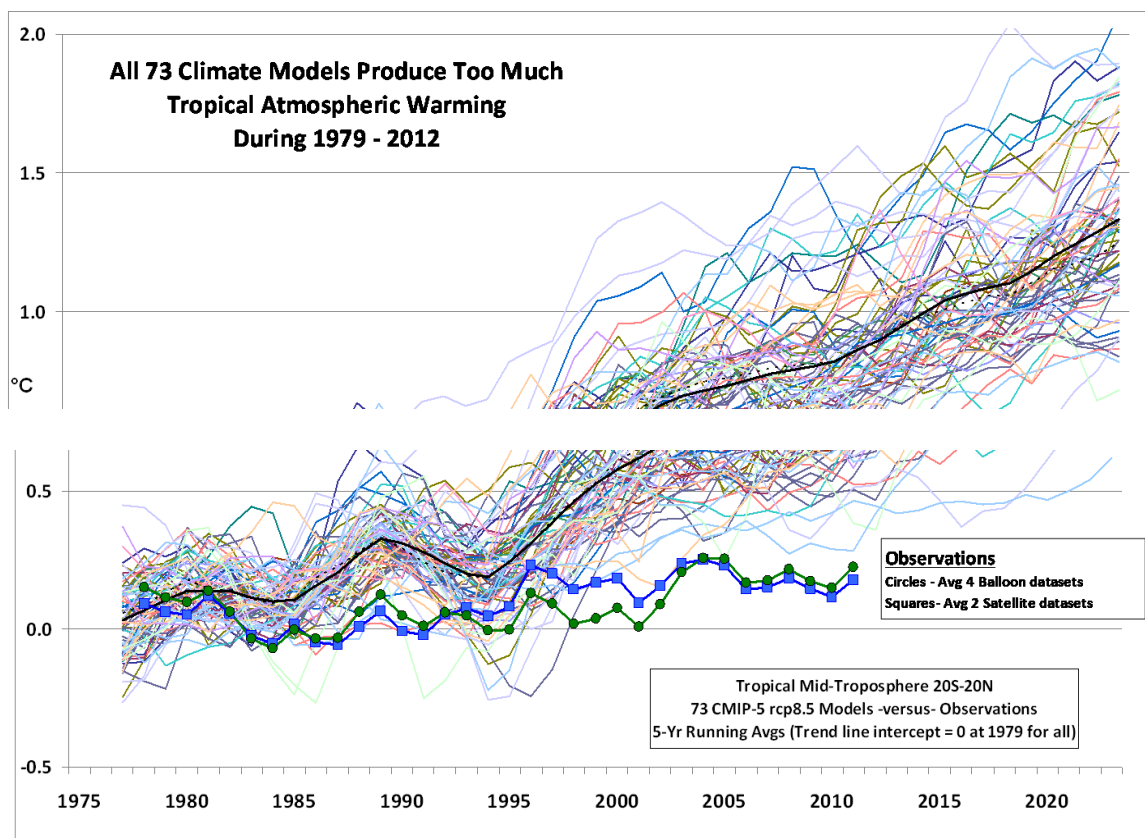


Figure 4.1.1.7. Mid-tropospheric (MT) temperature variations for the tropics (20°N to 20°S) in 73 current (CMIP5) climate models versus measurements from two satellite datasets and four weather balloon datasets. Adapted from Spencer, R.W. 2013. Statement to the U.S. Senate Environment and Public Works Committee, 19 July 2013, Washington, DC.

The fourth assumption made by the IPCC in its attribution of the late twentieth century rise in temperature to anthropogenic greenhouse gas increases is that the models correctly depict and account for natural variability. They most certainly do not, as evidenced by material presented in all of the chapters of this volume. The material presented in Section 4.2 emphasizes this point with respect to temperature, demonstrating repeatedly the reality of decadal, centennial, and millennial oscillations that occur naturally and are fully capable of explaining all of the warming experienced during the Current Warm Period. In addition, the warming of the global oceans to 2,000 m depth since the 1950s corresponds to a radiative energy imbalance of only 1 part in 1,000 (Levitus *et al.*, 2012), raising the question of whether scientists can attribute this small change to humans rather than nature.

Hundreds of peer-reviewed papers have presented evidence indicating temperatures of the past several decades are not unusual, unnatural, or unprecedented on a hemispheric or global scale. It is very likely the magnitude of prior warmth, such as what was experienced during both the Roman and Medieval Warm Periods, exceeded or was at least equal to the warmth of the Current Warm Period. Since temperatures were as warm back then, when atmospheric CO₂ concentrations were much lower than they are now, there are valid empirical reasons to conclude the temperature increase of the past century has occurred independently of the concomitant 40 percent increase in atmospheric CO₂. Real-world observations reveal the Current Warm Period is simply a manifestation of the natural progression of a persistent millennial-scale climate oscillation that regularly brings Earth several-hundred-year periods

of modestly higher and lower temperatures totally independent of variations in atmospheric CO₂ concentration.

Clearly, the IPCC's attribution of recent twentieth century warming to rising greenhouse gas concentrations is speculative at best.

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4.1.2 Urbanization Biases Still Taint Modern Temperature Records

The warming of near-surface air over non-urban areas of the planet during the past one to two centuries is believed to have been less than 1°C. Warming in many growing cities, on the other hand, may have been a full order of magnitude greater. Thus, since nearly all near-surface air temperature records of this period have been obtained from sensors located in population centers that have experienced significant growth, it is essential that urbanization-induced warming be removed from all original temperature records when attempting to accurately assess what has truly happened in the natural non-urban environment.

According to the IPCC, such urban influences have been mathematically accounted for and removed from the temperature records they utilize, effectively allowing them to conclude most of the remaining warming of the past few decades is the result of a human influence.

Recent studies confirm that effects of urbanization and land use change on the global temperature

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record are negligible (less than 0.006°C per decade over land and zero over the ocean) as far as hemispheric and continental-scale averages are concerned. All observations are subject to data quality and consistency checks to correct for potential biases. The real but local effects of urban areas are accounted for in the land temperature data sets used (Technical Summary of AR4, p. 36)

It is *likely* that urban heat-island effects and land use change effects have not raised the centennial global land surface air temperature trends by more than 10% of the observed trend. This is an average value; in some regions that have rapidly developed, urban heat island and land use change impacts on regional trends have been substantially larger (Second Order Draft of AR5, dated October 5, 2012, p. 2-4)

The 0.006°C per decade figure is presented as a research finding, but it is derived from mere conjecture. Section 2.3.3 of Brohan *et al.* (2006) states that to properly adjust the data would require a global comparison of urban versus rural records, but classifying records in this way is not possible since “no such complete meta-data are available” (p. 11), so the authors instead made an arbitrary assumption (p. 11) that the bias is no larger than 0.06 degrees per century.

As shown in the subsections below, filtering out urbanization and related land-use effects in the temperature record is a complicated task. There is solid evidence the methods currently used are inadequate, implying urbanization may account for a larger portion of the modern temperature rise than the IPCC acknowledges. Based on the studies reviewed below, it would appear almost certain surface-based temperature histories of the globe contain a significant warming bias introduced by insufficient corrections for the urban heat island effect. It may be impossible to make proper corrections for this deficiency, as the urban heat island effect of even small towns dwarfs any concomitant augmented greenhouse effect that may be present.

4.1.2.1 Global

Using a global dataset developed by Van Aardenne *et al.* (2001) that reveals the spatial distribution of levels of industrial activity over the planet as quantified by the intensity of anthropogenic CO₂ emissions, De Laat and Maurellis (2004) divided the surface of Earth into nonindustrial and industrial sectors of

various intensity levels. They then plotted the 1979–2001 temperature trends (°C/decade) of the sectors using data from the surface and the lower and middle troposphere. The two scientists determined “measurements of surface and lower tropospheric temperature change give a very different picture from climate model predictions and show strong observational evidence the degree of industrialization is correlated with surface temperature increases as well as lower tropospheric temperature changes.” They found the surface and lower tropospheric warming trends of all industrial regions were greater than the mean warming trend of Earth’s nonindustrial regions, and the difference in warming rate between the two types of land-use grows ever larger as the degree of industrialization increases.

De Laat and Maurellis note, “areas with larger temperature trends (corresponding to higher CO₂ emissions) cover a considerable part of the globe,” which implies “the ‘real’ global mean surface temperature trend is very likely to be considerably smaller than the temperature trend in the CRU [Hadley Center/Climate Research Unit] data,” since the temperature measurements in that database “are often conducted in the vicinity of human (industrial) activity.” These observations, they write, “suggest a hitherto-overlooked driver of local surface temperature increases, which is linked to the degree of industrialization” and lend “strong support to other indications that surface processes (possibly changes in land-use or the urban heat effect) are crucial players in observed surface temperature changes (Kalnay and Cai, 2003; Gallo *et al.*, 1996, 1999).” Thus they conclude “the observed surface temperature changes might be a result of local surface heating processes and not related to radiative greenhouse gas forcing.”

McKittrick and Michaels (2004) calculated 1979–2000 linear trends of monthly mean near-surface air temperature for 218 stations in 93 countries, using raw station data obtained from the Goddard Institute of Space Studies (GISS). They regressed the results against indicators of local economic activity such as income, gross domestic product growth rates, and coal use. They found, as expected, correlations between the spatial patterns of local socioeconomic measures and the magnitude of warming trends.

They repeated the process using the gridded surface air temperature data of the Climatic Research Unit (CRU) that had been adjusted to remove such effects. They found smaller but similar patterns that were statistically significant and added up to a net

warming bias, although they note “precise estimation of its magnitude will require further work.” Providing that estimation in a follow-up paper three years later, McKittrick and Michaels (2007) conclude the net warming bias accounted for “about half” of the estimated 1980–2002 global average temperature trend over land.

These and similar studies evidently posed a problem for the lead authors of the IPCC AR4, since their estimates of the magnitude of twentieth century warming and its attribution to GHGs relied on the assumption that the surface temperature record was more or less uncontaminated. For example, in one of the Climategate emails from IPCC Lead Author Phil Jones to his colleague Michael Mann, dated July 8, 2004, Jones confided he and IPCC coauthor Kevin Trenberth were determined to keep this evidence out of the IPCC report:

I can't see either of these papers being in the next IPCC report. Kevin [Trenberth] and I will keep them out somehow—even if we have to redefine what the peer-review literature is!

Consistent with that plan, no mention of these studies was made in the IPCC report drafts shown to reviewers. After the close of expert review, a statement was inserted into the published version (IPCC 2007, Chapter 3, p. 244) acknowledging the spatial pattern of warming matched that of industrialization but claiming “the correlation of warming with industrial and socioeconomic development ceases to be statistically significant” once the effects of atmospheric circulation changes are taken into account, a claim for which there was no supporting evidence. McKittrick (2010) subsequently tested the claim and showed it to be untrue. The U.S. Environmental Protection Agency nevertheless relied verbatim on this claim in its dismissal of comments on an endangerment finding related to greenhouse gas emissions (see <http://www.epa.gov/climatechange/endangerment/comments/volume2.html#2>).

Klotzbach *et al.* (2009) tested the data contamination issue in a different way. If there is no contamination of surface data due to land use changes, they noted, the difference between surface trends and satellite-based measures of the lower troposphere should be constant over time. But the trends diverge, and the divergence runs opposite to the direction predicted by climate models. They conclude contamination of the surface data through

land surface changes was a likely explanation.

Schmidt (2009) claims the McKittrick and Michaels results are likely spurious because of spatial autocorrelation in the temperature data, and he asserts it was unlikely similar patterns could be found across different climate datasets. He claims similar correlations could be found in GCM-generated data that, by construction, is not contaminated with urbanization. But Schmidt did not test his assertion about spatial autocorrelation, and his model-generated data failed to exhibit the claimed correlations.

McKittrick and Nierenberg (2010) tested Schmidt's conjectures in detail and showed them to be untrue. The evidence of data contamination was shown to be consistent across multiple combinations of surface and satellite data. It was not affected by spatial autocorrelation and it could not be replicated in data generated by the GISS climate model.

McKittrick and Tole (2012) went further and examined all 22 climate models used for the AR4, testing the models' ability to explain the spatial pattern of trends over 1979–2002, alone or in any linear combination, in comparison with indicators of urbanization and fixed geographical factors. After removing the 10 GCMs that generated predicted surface temperature trends anti-correlated with observations, they used Bayesian Model Averaging to evaluate 2¹⁹ possible linear combinations of explanatory models. They conclude only 2 of 22 climate models had significant explanatory power, and the optimal model of surface temperature changes required inclusion of measures of industrialization.

The IPCC also has relied on an argument by Parker (2004, 2006), who examined nighttime minimum urban temperature trends. He argues if urbanization had a significant effect, the observed warming would be less in a sample selected on nights with higher wind speed, but he found no such differences. He concludes urban warming could not be a significant factor in global averages. More recently, Wickham *et al.* (2013) tested the issue by partitioning the Berkeley Earth Surface Temperature (BEST) dataset using satellite-based measures of rural and urban locations and found no significant difference in average trends, likewise concluding land surface changes could not be a factor in global average trends.

Neither of these approaches addressed the evidence in the original McKittrick and Michaels (2004, 2007) studies. McKittrick (2013) demonstrated a Parker-type result, with equivalent trends on calm and windy nights, could be replicated on a dataset

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known on independent grounds to be contaminated with strong urbanization effects. And he demonstrated the Wickham *et al.* methodology was defective because their results were consistent either with the absence of an urbanization bias or its presence, and a more detailed statistical model would be required to determine which actually was the case.

That an urban heat island-induced error has indeed corrupted databases claimed to be immune from it is also suggested by the work of Hergerl and Wallace (2000), who attempted to determine whether trends in recognizable atmospheric modes of variability could account for all or part of the observed trend in surface-troposphere temperature differential; i.e., lapse rate, which has been driven by the upward-inclined trend in surface-derived temperatures and the nearly level trend in satellite-derived tropospheric temperatures over the last two decades of the twentieth century.

The two researchers found “modes of variability that affect surface temperature cannot explain trends in the observed lapse rate,” and “no mechanism with clear spatial or time structure can be found that accounts for that trend.” In addition, they acknowledge “all attempts to explain all or a significant part of the observed lapse rate trend by modes of climate variability with structured patterns from observations have failed,” and “an approach applying model data to isolate such a pattern has also failed.” Nor could they find any evidence “that interdecadal variations in radiative forcing, such as might be caused by volcanic eruptions, variations in solar output, or stratospheric ozone depletion alone, offer a compelling explanation.” They conclude, “there remains a gap in our fundamental understanding of the processes that cause the lapse rate to vary on interdecadal timescales.”

One reason no meteorological or climatic explanation could be found for the ever-increasing difference between the surface- and satellite-derived temperature trends of the past 20-plus years may be that one of the temperature records is incorrect. Faced with this possibility, one might want to determine which of the records is likely to be erroneous and then assess the consequences of that determination. Although this task may seem daunting, it is not that difficult. Hergerl and Wallace found good correspondence between the satellite and radiosonde temperature trends, leaving little reason to doubt the veracity of the satellite results, since this comparison essentially amounts to an *in situ* validation of the satellite record. It would be easy for a spurious

warming of 0.12°C per decade to be introduced into the surface air temperature trend as a consequence of the worldwide intensification of the urban heat island effect likely driven by the worldwide population increase that manifested in most of the places where surface air temperature measurements were made over the last two decades of the twentieth century.

Other scientists have considered whether the urban heat island is affected by the direct heating of near-surface air in towns and cities by the carbon dioxide dome that occurs above them. Balling *et al.* (2002) obtained vertical profiles of atmospheric CO₂ concentration, temperature, and humidity over Phoenix, Arizona from measurements made in association with once-daily aircraft flights conducted over a 14-day period in January 2000 that extended through, and far above, the top of the city’s urban CO₂ dome during the times of the latter’s maximum manifestation. They employed a one-dimensional infrared radiation simulation model to determine the thermal impact of the urban CO₂ dome on the near-surface temperature of the city.

The researchers found the CO₂ concentration of the air over Phoenix dropped off rapidly with altitude, returning from a central-city surface value on the order of 600 ppm to a normal non-urban background value of approximately 378 ppm at an air pressure of 800 hPa, creating a calculated surface warming of only 0.12°C at the time of maximum CO₂-induced warming potential, about an order of magnitude less than the urban heat island effect of cities the size of Phoenix. The authors conclude the warming induced by the urban CO₂ dome of Phoenix is possibly two orders of magnitude smaller than what is produced by other sources of the city’s urban heat island. Although human activities are indeed responsible for high urban air temperatures, which can rise 10°C or more above those of surrounding rural areas, these high values are not the result of a local CO₂-enhanced greenhouse effect.

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4.1.2.2 Asia

In a study of the urban heat island effect in South Korea, Choi *et al.* (2003) compare the mean station temperatures of three groupings of cities (one comprised of four large urban stations with a mean 1995 population of 4,830,000, one of six smaller urban stations with a mean 1995 population of 548,000, and one of six “rural” stations with a mean 1995 population of 214,000) over the period 1968–1999. They found the “temperatures of large urban stations exhibit higher urban bias than those of smaller urban stations and that the magnitude of urban bias has increased since the late 1980s.” They note “estimates of the annual mean magnitude of urban bias range from 0.35°C for smaller urban stations to 0.50°C for large urban stations,” concluding “none of the rural stations used for this study can represent a true non-urbanized environment.” They say their results are underestimates of the true urban effect, and “urban growth biases are very serious in South Korea and must be taken into account when assessing the reliability of temperature trends.”

In a second study conducted in South Korea, Chung *et al.* (2004a) report there was an “overlapping of the rapid urbanization-industrialization period with the global warming era,” and the background climatic trends from urbanized areas might therefore be contaminated by a growing urban heat island effect. To investigate this possibility, “monthly averages of daily minimum, maximum, and mean temperature at 14 synoptic stations were prepared for 1951–1980 (past normal) and 1971–2000 (current normal) periods,” and “regression equations were used to determine potential effects of urbanization and to extract the net contribution of regional climate change to the apparent temperature change.” Twelve of these stations were growing urban sites of various size, and two (where populations actually decreased) were rural, one being located inland and one on a remote island.

Over the 20 years that separated the two normal periods, Chung *et al.* report that in Seoul, where population increase was greatest, annual mean daily minimum temperature increased by 0.7°C, while a 0.1°C increase was detected at one of the two rural sites and a 0.1°C decrease was detected at the other, for no net change in their aggregate mean value. In the case of annual mean daily maximum temperature, a 0.4°C increase was observed at Seoul and a 0.3°C increase was observed at the two rural sites. Thus the change in the annual mean daily mean temperature was an increase of 0.15°C at the two rural sites, indicative of regional background warming of 0.075°C per decade. The change of annual mean daily mean temperature at Seoul was an increase of 0.55°C, or 0.275°C per decade, indicative of an urban-induced warming of 0.2°C per decade in addition to the regional background warming of 0.075°C per decade. Corresponding results for urban areas of intermediate size defined a linear relationship that connected these two extreme results when plotted against the logarithm of population increase over the two-decade period.

In light of the significantly intensifying urban heat island effect detected in their study, Chung *et al.* say it is “necessary to subtract the computed urbanization effect from the observed data at urban stations in order to prepare an intended nationwide climatic atlas,” noting “rural climatological normals should be used instead of the conventional normals to simulate ecosystem responses to climatic change, because the urban area is still much smaller than natural and agricultural ecosystems in Korea.”

Chung *et al.* (2004b) evaluated temperature

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changes at ten urban and rural Korean stations over the period 1974–2002. They found “the annual temperature increase in large urban areas was higher than that observed at rural and marine stations.” Specifically, they note, “during the last 29 years, the increase in annual mean temperature was 1.5°C for Seoul and 0.6°C for the rural and seashore stations,” while increases in mean January temperatures ranged from 0.8 to 2.4°C for the ten stations. In addition, they state, “rapid industrialization of the Korean Peninsula occurred during the late 1970s and late 1980s,” and when plotted on a map, “the remarkable industrialization and expansion ... correlate[s] with the distribution of increases in temperature.” Consequently, Chung *et al.* (2004b) found much, and in many cases most, of the warming experienced over the past several decades in the urban areas of Korea was the result of local urban influences not indicative of regional background warming.

Kim and Kim (2011) derived values of the total warming for cities on the Korean peninsula with temperature data from four cities covering the period 1909–2008, 12 cities covering 1954–2008, and 20 cities covering 1969–2008. Values of the urban warming effect were derived “by using the warming mode of Empirical Orthogonal Function (EOF) analysis of the 55 years of temperature data from 1954 to 2008.” The estimated amounts of urban warming were verified by means of a multiple linear regression equation with two independent variables: rate of population growth and total population. By subtracting the temperature increase due to urbanization from the total temperature increase of each city, they obtained what they call “greenhouse warming,” although it should more appropriately be identified as background warming, natural warming, or non-urban-induced warming, because forcings other than greenhouse gases may play a major role in the non-urban-induced portion of the total observed warming.

Kim and Kim report the mean total warming of the 12 cities over the period 1954–2008 was 1.37°C, of which 0.77°C was due to the growth of their urban heat islands and the remaining 0.60°C was due to other factors. In addition, they found “urban warming depends more on the population percent growth rate than the average population.” In the case of Pohang and Incheon, for example, which “have rapidly increasing populations due to rapid industrialization,” they note “the degree of urbanization was great.” In the case of Busan, which has a large and steady population, they discovered “the degree of

urbanization was weak.” Thus “the rising trend of temperature appeared stronger in newly industrialized cities more than in large cities.”

Weng (2001) evaluated the effect of land cover changes on surface temperatures of the Zhujiang Delta (an area of slightly more than 17,000 km²) via a series of analyses of remotely sensed Landsat Thematic Mapper data. They found between 1989 and 1997 the area of land devoted to agriculture declined by nearly 50 percent, while urban land area increased by close to the same percentage. After normalizing the surface radiant temperature for the years 1989 and 1997, they used image differencing to produce a radiant temperature change image, which they overlaid with images of urban expansion. The results indicated “urban development between 1989 and 1997 has given rise to an average increase of 13.01°C in surface radiant temperature.”

Chen *et al.* (2003) evaluated several characteristics of Shanghai’s urban heat island, including its likely cause, based on analyses of monthly meteorological data from 1961 to 1997 at 16 stations in and around this hub of economic activity that is one of the most flourishing urban areas in all of China. Defining the urban heat island of Shanghai as the mean annual air temperature difference between urban Longhua and suburban Songjiang, Chen *et al.* found its strength increased in essentially linear fashion from 1977 to 1997 by 1°C.

Chen *et al.* conclude “the main factor causing the intensity of the heat island in Shanghai is associated with the increasing energy consumption due to economic development,” noting in 1995 the Environment Research Center of Peking University determined the annual heating intensity due to energy consumption by human activities was approximately 25 Wm⁻² in the urban area of Shanghai but only 0.5 Wm⁻² in its suburbs. In addition, they point out the 0.5°C/decade intensification of Shanghai’s urban heat island is an order of magnitude greater than the 0.05°C/decade global warming of Earth over the past century, suggesting the ongoing intensification of even already-strong urban heat islands cannot be discounted.

Kalnay and Cai (2003) used differences between trends in directly observed surface air temperature and trends determined from the NCEP-NCAR 50-year Reanalysis (NNR) project (based on atmospheric vertical soundings derived from satellites and balloons) to estimate the impact of land-use changes on surface warming. Over undisturbed rural areas of the United States, they found the surface- and

reanalysis-derived air temperature data yielded essentially identical trends, implying differences between the two approaches over urban areas would represent urban heat island effects. Zhou *et al.* (2004) applied the same technique over southeast China, using an improved version of reanalysis that includes newer physics, observed soil moisture forcing, and a more accurate characterization of clouds.

For the period January 1979 to December 1998, the eight scientists derived an “estimated warming of mean surface [air] temperature of 0.05°C per decade attributable to urbanization,” which they say “is much larger than previous estimates for other periods and locations, including the estimate of 0.027°C for the continental U.S. (Kalnay and Cai, 2003).” They note, however, because their analysis “is from the winter season over a period of rapid urbanization and for a country with a much higher population density, we expect our results to give higher values than those estimated in other locations and over longer periods.”

Zhang *et al.* (2005) used the approach of Kalnay and Cai (2003) to determine the impacts of land-use changes on surface air temperature throughout eastern China (east of 110°E), where rapid urbanization, deforestation, desertification, and other changes in land use have occurred over the past quarter-century, focusing on daily mean, maximum, and minimum air temperatures from 259 stations over the period 1960–1999. Their analyses indicate changes in land use had little or no influence on daily maximum temperatures, but they explain about 18 percent of the observed daily mean temperature increase and 29 percent of the observed daily minimum temperature increase in this region over the past 40 years, yielding decadal warming trends of about 0.12°C and 0.20°C for these two parameters, respectively.

Frauenfeld *et al.* (2005) used daily surface air temperature measurements from 161 stations located throughout the Tibetan Plateau (TP) to calculate the region’s mean annual temperature for each year from 1958 through 2000, plus 2-meter temperatures from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40), which “are derived from rawinsonde profiles, satellite retrievals, aircraft reports, and other sources including some surface observations.” This approach, they write, results in “more temporally homogeneous fields” that provide “a better assessment of large-scale temperature variability across the plateau.” Over the period 1958–2000, Frauenfeld *et al.* report, “time series based on aggregating all station data on the TP show a statistically significant positive trend of 0.16°C per

decade,” as also has been reported by Liu and Chen (2000). However, they state, “no trends are evident in the ERA-40 data for the plateau as a whole.”

In discussing this discrepancy, the three scientists suggest “a potential explanation for the difference between reanalysis and station trends is the extensive local and regional land use change that has occurred across the TP over the last 50 years.” They note, for example, “over the last 30 years, livestock numbers across the TP have increased more than 200% due to inappropriate land management practices and are now at levels that far exceed the carrying capacity of the region (Du *et al.*, 2004).” The resultant overgrazing, they write, “has caused land degradation and desertification at an alarming rate (Zhu and Li, 2000; Zeng *et al.*, 2003),” and “in other parts of the world, land degradation due to overgrazing has been shown to cause significant local temperature increases (e.g., Balling *et al.*, 1998).”

They also note “urbanization, which can result in 8°–11°C higher temperatures than in surrounding rural areas (e.g., Brandsma *et al.*, 2003), has also occurred extensively on the TP,” as “construction of a gas pipeline in the 1970s and highway expansion projects in the early 1980s have resulted in a dramatic population influx from other parts of China, contributing to both urbanization and a changed landscape.” Thus they state, “the original Tibetan section of Lhasa (i.e., the pre-1950 Lhasa) now only comprises 4% of the city, suggesting a 2400% increase in size over the last 50 years.” And they note “similar population increases have occurred at other locations across the TP,” and “even villages and small towns can exhibit a strong urban heat island effect.”

Frauenfeld *et al.* contend “these local changes are reflected in station temperature records.” We agree, and we note when the surface-generated anomalies are removed, as in the case of the ERA-40 reanalysis results they present, it is clear there has been no warming of the Tibetan Plateau since at least 1958. Other results reported in this section imply much the same about other parts of China and greater Asia. Thus the dramatic surface-generated late twentieth century warming of the world claimed by the IPCC, Mann *et al.* (1998, 1999), and Mann and Jones (2003) to represent mean global background conditions likely significantly overestimates the warming over the past 30 years and is therefore not a true representation of Earth’s recent temperature history.

Based on temperature data obtained at the “national reference and basic stations” at Beijing and Wuhan, China, plus similar data from six rural

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stations near Beijing and four rural stations near Wuhan, Ren *et al.* (2007) calculated the rates of temperature rise over the periods 1961–2000 and 1981–2000 to determine what portion of the observed warming at these stations is truly background warming and what is spurious, urban-induced warming.

The authors determined the rate of increase in annual mean surface air temperature over the period 1961–2000 was 0.32°C/decade and 0.31°C/decade, respectively, for Beijing and Wuhan, but only 0.06°C/decade and 0.11°C/decade for the corresponding sets of rural stations that surround them. Spurious urban warming was responsible for more than 80 percent of the 1961–2000 temperature increase at Beijing and a little more than 64 percent of the temperature increase at Wuhan. For the period 1981–2000, spurious urban warming accounted for 61 percent of the Beijing temperature increase and 40 percent of the Wuhan increase. The researchers also report the Beijing and Wuhan stations are not located in the central parts of the cities, and their findings are thus not representative of the cities' downtown areas, where urban heat island effects would be expected to be even greater.

Ren *et al.* note the impact of urbanization on the surface air temperature trends of the two mega-city stations is much larger than what is reported for North China as a whole and for Hubei Province. Consequently, they conclude “it is likely that a larger part of the surface air temperature increase in the country as obtained from ... national reference and basic stations has been caused by [an] enhanced urban heat island effect during the past decades.” They say there is “a need for paying more attention to the selection of observational sites, and for further detecting and adjusting the urbanization-induced bias probably existing in surface air temperature records of city stations.”

Ren *et al.* (2008) employed a dataset obtained from 282 meteorological stations, including all of the ordinary and national basic and reference weather stations of north China, to determine the urbanization effect on surface air temperature trends of that part of the country over the period 1961–2000. They categorized the stations based on city size expressed in millions of people: rural (<0.05), small city (0.01–0.10), medium city (0.10–0.50), large city (0.50–1.00), and metropolis (>1.00). They found mean annual surface air temperature trends over the period, in degrees C per decade, were 0.18 (rural), 0.25 (small city), 0.28 (medium city), 0.34 (large city),

0.26 (metropolis), and 0.29 (national), making the urban-induced component of the warming trend 0.07 (small city), 0.10 (medium city), 0.16 (large city), 0.08 (metropolis), and 0.11 (national), all of which are significant at the 0.01 level. The seven Chinese researchers conclude it is “obvious that, in the current regional average surface temperature series in north China, or probably in the country as a whole, there still remain large effects from urban warming,” noting “the contribution of urban warming to total annual mean surface air temperature change as estimated with the national basic/reference dataset reaches 37.9%.”

Yang *et al.* (2011) note the IPCC's *Fourth Assessment Report* states urban heat island (UHI) effects are real but only “local and have a negligible influence on global warming trends.” However, Yang *et al.* write, the UHI effect is regarded by others “as one of the major errors or sources of uncertainty in current surface warming studies,” citing Gong and Wang (2002) and Heisler and Brazel (2010). They state, “some research results indicate that this effect may play a more significant role in temperature trends estimated at multiple geographic scales,” noting Pielke (2005) and Stone (2009) suggest “such results should be accorded more consideration in the mitigation of climate change.”

Yang *et al.* use monthly mean surface air temperature data from 463 meteorological stations, including those from the 1981–2007 ordinary and national basic reference surface stations in east China and from the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) Reanalysis, to investigate the effect of rapid urbanization on temperature change for six different categories of population size or density—metropolis, large city, medium-sized city, small city, suburban, and rural—as determined from satellite-measured nighttime light imagery and census data. The three researchers state their findings indicate “rapid urbanization has a significant influence on surface warming over east China,” noting, “overall, UHI effects contribute 24.2% to regional average warming trends” and “the strongest effect of urbanization on annual mean surface air temperature trends occurs over the metropolis and large city stations, with corresponding contributions of about 44% and 35% to total warming, respectively,” with UHI trends of 0.398°C and 0.26°C per decade. They also say the UHI warming trends and their contributions to the overall warming over east China provided in their paper “can still be

regarded as conservative.”

If such UHI trends continue, the Chinese scientists conclude, “certain metropolitan areas may experience a rate of warming well beyond the range projected by the global climate change scenarios of the IPCC,” referencing Stone (2007), while adding, “the increasing divergence between urban and rural surface temperature trends highlights the limitations of the response policy to climate change [that] focus only on greenhouse gas reduction,” citing Stone (2009).

Zhou and Ren (2011) used the daily temperature records of 526 measurement stations included among the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration to evaluate trends in 15 extreme temperature indices for the period 1961–2008. Based on the earlier findings of Zhou and Ren (2009), which indicated the contribution of urban warming to overall warming often exceeded 50 percent, they adjusted their results to account for the impact of each site’s urban heat island effect.

They 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.”

Regarding the urban heat island phenomenon, the two researchers conclude their paper by stating “more attention needs to be given to the issue in future studies.”

Gao and Liu (2012) studied the effect of the deforestation of portions of Heilongjiang Province in Northeast China, which has an annual temperature ranging from -4°C to $+4^{\circ}\text{C}$, with its winters being “long and frigid” and its summers “short and cool.” Their study covered two periods: 1958–1980, when forest cover was reduced from 238,335 km^2 to

216,009 km^2 ; and 1980–2000, when forest cover was further reduced to 207,629 km^2 . Over the entire period the two researchers analyzed (1958–2000), there was a nationwide warming of 0.99°C , whereas the annual temperature of Heilongjiang Province rose by 1.68°C , which suggests a concomitant deforestation-induced warming of 0.69°C . Thus, in response to the 13 percent reduction in forest cover over the 42-year interval Gao and Liu analyzed, the mean annual temperature of Heilongjiang Province rose by 0.69°C , a substantial amount considering the temperature of the globe had risen by an average of only about 0.7°C since the start of the Industrial Revolution.

Tokairin *et al.* (2010) note the population of Jakarta, the capital of Indonesia, was approximately 12 million in 2000, whereas it had been about 5 million in the 1970s. They note the rapid population increase of the past few decades brought a rapid expansion of the city’s urban area, adding to the strength of the urban heat island of the original “old city” of the 1970s. To evaluate the warming power of the newer infrastructure added around the central old city, Tokairin *et al.* analyzed the air temperature increase in the initially urbanized area of Jakarta over the 30-year period between the 1970s and the 2000s, using air temperature data provided by the country’s National Climatic Data Center. They made a rough estimate of the sensible heat in the old city during the 2000s that originated in, and was transported from, the newly developed urban area.

The three researchers report “the sea breeze developed at an earlier time of day in the present day than in the 1970s” and “in the present-day case, a converging flow developed over the old city in association with the low pressure which formed over the same location.” They further note “the daytime average and maximum air temperature in the old city were higher in the present day than in the 1970s by 0.6 and 0.9°C , respectively, due to the advection of heat from the new area” and “the amount of heat advected into the old city was estimated to be -0.7 Wm^{-2} in the 1970s and 77 Wm^{-2} in the 2000s.”

Fujibe (2011) writes, “in the context of global climate change, urban warming can bias results obtained for background monitoring, as many of the observatories that have been in operation for a long time are located in cities.” Nevertheless, Fujibe notes, the IPCC (2007) has suggested “the globally averaged temperature trend is hardly affected by urbanization.” Unconvinced of the validity of the IPCC’s assertion, the Japanese researcher reviews what is known about

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the subject based on research conducted in Japan.

Fujibe reports “the recorded rate of temperature increase is a few degrees per century in large cities and tends to be larger at night than during the daytime.” In some cities, “the increase in annual extreme minimum temperature exceeds 10°C per century.” Fujibe notes numerous studies have detected heat islands in small settlements “with a population of 1000 or less,” as reported by Tamiya (1968), Tamiya and Ohyama (1981), Sakakibara and Morita (2002), Sakakibara and Kitahara (2003), and Sakakibara and Matsui (2005), where statistically significant trends on the order of 0.04°C per decade have been observed. Fujibe concludes, “urban warming can be a biasing factor that may contaminate data used for monitoring the background temperature change,” with locations with low population densities of 100–300 people per square kilometer “showing a statistically significant anomalous trend of 0.04°C per decade.”

Clearly, a substantial part of the past half-century’s global warming, which the IPCC attributes to the greenhouse effect of CO₂ and methane, is nothing more than a manifestation of the well-known urban heat island effect, which is not properly removed from the various databases discussed here and probably many others. If such spurious warming is not accounted and appropriately adjusted for, public and scientific confidence in the quality of global temperature datasets will continue to decline.

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4.1.2.3 North America

In studying the urban heat island (UHI) of Houston, Texas, Streutker (2003) analyzed 82 sets of nighttime radiation data obtained from the split-window infrared channels of the Advanced Very High Resolution Radiometer on board the NOAA-9 satellite during March 1985 through February 1987 and from 125 sets of similar data obtained from the NOAA-14 satellite during July 1999 through June 2001. Between these two periods, the mean nighttime surface temperature of Houston rose by 0.82 ± 0.10 °C. In addition, Streutker notes the growth of the Houston UHI, both in magnitude and spatial extent, “scales roughly with the increase in population,” and the mean rural temperature measured during the second interval was “virtually identical to the earlier interval.”

Streutker’s work demonstrates the UHI phenomenon can be very powerful, for in just 12 years the UHI of Houston grew by more than the IPCC contends the mean surface air temperature of the planet rose over the entire past century, when Earth’s population rose by approximately 280

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percent, or nearly an order of magnitude more than the 30 percent population growth experienced by Houston over the 12 years of Streutker's study.

Maul and Davis (2001) analyzed air and seawater temperature data obtained over the past century at the sites of several primary tide gauges maintained by the U.S. Coast and Geodetic Survey. Noting each of these sites "experienced significant population growth in the last 100 years," and "with the increase in maritime traffic and discharge of wastewater one would expect water temperatures to rise" (due to a maritime analogue of the urban heat island effect), they calculated trends for the 14 longest records and derived a mean century-long seawater warming of 0.74°C , with Boston registering an anomalous 100-year warming of 3.6°C . In addition, they report air temperature trends at the tide gauge sites, which represent the standard urban heat island effect, were "much larger" than the seawater temperature trends.

Dow and DeWalle (2000) analyzed trends in annual evaporation and Bowen ratio measurements on 51 eastern U.S. watersheds that experienced various degrees of urbanization between 1920 and 1990. They determined as residential development progressively occurred on what originally were rural watersheds, watershed evaporation decreased and sensible heating of the atmosphere increased. And from relationships derived from the suite of watersheds investigated, they calculated complete transformation from 100 percent rural to 100 percent urban characteristics resulted in a 31 percent decrease in watershed evaporation and a 13 Wm^{-2} increase in sensible heating of the atmosphere.

Climate modeling exercises suggest a doubling of the air's CO_2 concentration will result in a nominal 4 Wm^{-2} increase in the radiative forcing of Earth's surface-troposphere system, which often has been predicted to produce an approximate 4°C increase in the mean near-surface air temperature of the globe, indicative of an order-of-magnitude climate sensitivity of 1°C per Wm^{-2} change in radiative forcing. Thus, to a first approximation, the 13 Wm^{-2} increase in the sensible heating of the near-surface atmosphere produced by the total urbanization of a pristine rural watershed in the eastern United States reported by Dow and DeWalle could be expected to produce an increase of about 13°C in near-surface air temperature over the central portion of the watershed, which is consistent with maximum urban heat island effects observed in large and densely populated cities. Therefore, a 10 percent rural-to-urban transformation could produce a warming on the order of 1.3°C , and a

mere 2 percent transformation could increase the near-surface air temperature by as much as a quarter of a degree Centigrade.

This powerful anthropogenic but non-greenhouse-gas-induced effect of urbanization on the energy balance of watersheds and the temperature of the boundary-layer air above them begins to express itself with the very first hint of urbanization and, hence, may be readily overlooked in studies seeking to identify a greenhouse-gas-induced global warming signal. In fact, the fledgling urban heat island effect already may be present in many temperature records routinely been considered "rural enough" to be devoid of all human influence, when in fact that may be far from the truth.

A case in point is provided by the study of Changnon (1999), who used a series of measurements of soil temperatures obtained in a completely rural setting in central Illinois between 1889 and 1952 and a contemporary set of air temperature measurements made in an adjacent growing community (plus similar data obtained from other nearby small towns) to evaluate the magnitude of unsuspected heat island effects that might be present in small towns and cities typically assumed to be free of urban-induced warming. This work revealed soil temperature in the completely rural setting increased by 0.4°C between the decade of 1901–1910 and 1941–1950.

This warming is 0.2°C less than the 0.6°C warming determined for the same time period from the entire dataset of the U.S. Historical Climatology Network, which is supposedly corrected for urban heating effects. It is also 0.2°C less than the 0.6°C warming determined for this time period by 11 benchmark stations in Illinois with the highest-quality long-term temperature data, all of which are located in communities with populations of less than 6,000 people as of 1990. And it is 0.17°C less than the 0.57°C warming derived from data obtained at the three benchmark stations closest to the site of the soil temperature measurements and with populations of less than 2,000 people.

Changnon states his findings suggest "both sets of surface air temperature data for Illinois believed to have the best data quality with little or no urban effects may contain urban influences causing increases of 0.2°C from 1901 to 1950." He further notes "this could be significant because the IPCC (1995) indicated that the global mean temperature increased 0.3°C from 1890 to 1950."

Clearly, the efforts of this world-renowned climate specialist call all near-surface global air

temperature histories into question. Until the influence of very-small-town urban heat island effects is identified and accounted for, the so-called “unprecedented” global warming of the past century, and especially the past quarter-century, cannot be accepted at face value.

DeGaetano and Allen (2002b) used data from the U.S. Historical Climatology Network to calculate trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th percentile across the United States over the period 1960–1996. In the case of daily warm minimum temperatures, the slope of the regression line fit to the data of a plot of the annual number of 95th percentile exceedences vs. year was found to be 0.09 exceedences 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 rate of increase at rural stations less affected by growing urban heat islands. The rate of increase in the annual number of daily maximum temperature 95th percentile exceedences per year over the same time period was found to be 50 percent greater at urban stations than at rural stations.

Balling and Idso (2002) analyzed and compared temperature trends for the period 1979–2000 in the conterminous United States using six temperature databases:

- the unadjusted temperature data of the United States Historical Climatology Network (RAW);
- the RAW data adjusted for (a) time of observation biasing, (b) changes to the new maximum/minimum temperature system equipment, (c) station history, including other instrument adjustments, and (d) an interpolation scheme for estimating missing data from nearby highly correlated station records (FILNET);
- essentially the FILNET data adjusted for urbanization effects (URB-ADJ);
- the updated dataset developed by Jones (1994) of the University of East Anglia (IPCC);
- the satellite-based lower-tropospheric temperature dataset (MSU2LT); and
- the radiosonde (balloon-based) temperature data that comprised “the surface reading taken the

moment the balloon is launched,” which “typically occurs near 1.5 m above the surface, which is near the shelter heights used in the USHCN data set” (SONDE).

In comparing the difference between the FILNET and RAW temperature trends, Balling and Idso found a nearly monotonic increase of more than 0.05°C per decade, which they found to be highly significant at the 0.0001 level of confidence. In addition, they found “the trends in the unadjusted temperature records [were] not different from the trends of the independent satellite-based lower-tropospheric temperature record or from the trend of the balloon-based near-surface measurements.” The two Arizona State University Office of Climatology researchers state the adjustments made to the raw USHCN temperature data were “producing a statistically significant, but spurious, warming trend” that “approximates the widely-publicized 0.50°C increase in global temperatures over the past century.”

Hinkel *et al.* (2003) installed 54 temperature-recording instruments on the Arctic Coastal Plain near the Chuckchi Sea at Barrow, Alaska in mid-June of 2001, half within the urban area and the other half distributed across approximately 150 km² of surrounding land, all of which provided air temperature data at hourly intervals approximately two meters above the surface of the ground. They describe the area as “the northernmost settlement in the USA and the largest native community in the Arctic,” the population of which “has grown from about 300 residents in 1900 to more than 4600 in 2000.”

Based on urban-rural spatial averages for the entire winter period (December 2001–March 2002), the four researchers determined the urban area to be 2.2°C warmer than the rural area. During this period, the mean daily urban-rural temperature difference increased with decreasing temperature, “reaching a peak value of around 6°C in January–February.” They also determined the daily urban-rural temperature difference increased with decreasing wind speed, such that under calm conditions (< 2 m s⁻¹) the daily urban-rural temperature difference was 3.2°C in the winter. Finally, under simultaneous calm and cold conditions, the urban-rural temperature difference was observed to achieve hourly magnitudes exceeding 9°C.

For the period December 1 to March 31 of four consecutive winters, Hinkel and Nelson (2007) report the spatially averaged temperature of the urban area of Barrow was about 2°C warmer than that of the

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rural area, and it was not uncommon for the daily magnitude of the urban heat island to exceed 4°C. On some days, they note, the magnitude of the urban heat island exceeded 6°C, and values in excess of 8°C were sometimes recorded. The warmest individual site temperatures were “consistently observed in the urban core area,” they report.

These findings indicate just how difficult it is to measure a background global temperature increase believed to have been less than 1°C over the past century (representing a warming of less than 0.1°C per decade), when the presence of a mere 4,500 people can create a winter heat island two orders of magnitude greater than the signal being sought. Temperature measurements made within the range of influence of even a small village cannot be adjusted to the degree of accuracy required to reveal the true magnitude of the pristine rural temperature change.

Ziska *et al.* (2004) characterized the gradual changes that occur in a number of environmental variables as one moves from a rural location (a farm approximately 50 km from the city center of Baltimore, Maryland) to a suburban location (a park approximately 10 km from the city center) to an urban location (the Baltimore Science Center, approximately 0.5 km from the city center). At each of these locations, four 2 x 2 m plots were excavated to a depth of about 1.1 m, after which they were filled with identical soils, the top layers of which contained seeds of naturally occurring plants of the area. These seeds sprouted in the spring of the year, and the plants they produced were allowed to grow until they senesced in the fall, after which all were cut at ground level, removed, dried, and weighed.

Along the rural-to-suburban-to-urban transect, the only consistent differences in the environmental variables they measured were a rural-to-urban increase of 21 percent in average daytime atmospheric CO₂ concentration and increases of 1.6 and 3.3°C in maximum (daytime) and minimum (nighttime) daily temperatures, respectively. These changes, they write, are “consistent with most short-term (~50 year) global change scenarios regarding CO₂ concentration and air temperature.” They state, “productivity, determined as final above-ground biomass, and maximum plant height were positively affected by daytime and soil temperatures as well as enhanced CO₂, increasing 60 and 115% for the suburban and urban sites, respectively, relative to the rural site.”

George *et al.* (2007) reported on five years of work at the same three transect locations near

Baltimore, stating, “atmospheric CO₂ was consistently and significantly increased on average by 66 ppm from the rural to the urban site over the five years of the study,” and “air temperature was also consistently and significantly higher at the urban site (14.8°C) compared to the suburban (13.6°C) and rural (12.7°C) sites.” They note the increases in atmospheric CO₂ and air temperature they observed “are similar to changes predicted in the short term with global climate change, therefore providing an environment suitable for studying future effects of climate change on terrestrial ecosystems,” specifically pointing out, “urban areas are currently experiencing elevated atmospheric CO₂ and temperature levels that can significantly affect plant growth compared to rural areas.”

LaDochy *et al.* (2007) report, “when speculating on how global warming would impact the state [of California], climate change models and assessments often assume that the influence would be uniform (Hansen *et al.*, 1998; Hayhoe *et al.*, 2004; Leung *et al.*, 2004).” To assess the validity of this assumption, they calculated temperature trends over the 50-year period 1950–2000 to explore the extent of warming in various subregions of the state. They then evaluated the influence of human-induced changes to the landscape on the observed temperature trends and determined their significance compared to those caused by changes in atmospheric composition, such as the air’s CO₂ concentration.

The three researchers found “most regions showed a stronger increase in minimum temperatures than with mean and maximum temperatures,” and “areas of intensive urbanization showed the largest positive trends, while rural, non-agricultural regions showed the least warming.” They report the Northeast Interior Basins of the state experienced cooling. Large urban sites, by contrast, exhibited rates of warming “over twice those for the state, for the mean maximum temperature, and over five times the state’s mean rate for the minimum temperature.” They conclude, “if we assume that global warming affects all regions of the state, then the small increases seen in rural stations can be an estimate of this general warming pattern over land,” which implies “larger increases,” such as those they observed in areas of intensive urbanization, “must then be due to local or regional surface changes.”

Rosenzweig *et al.* (2009) compared “the possible effectiveness of heat island mitigation strategies to increase urban vegetation, such as planting trees or incorporating vegetation into rooftops, with strategies

to increase the albedo of impervious surfaces.” They report, “surface air temperatures elevated by at least 1°C have been observed in New York City for more than a century (Rosenthal *et al.*, 2003; Gaffin *et al.*, 2008), and the heat island signal, measured as the difference between the urban core and the surrounding rural surface air temperature readings taken at National Weather Service stations, averages ~4°C on summer nights (Kirkpatrick and Shulman, 1987; Gedzelman *et al.*, 2003; Gaffin *et al.*, 2008).” The greatest temperature differences typically were sustained “between midnight and 0500 Eastern Standard Time (EST; Gaffin *et al.*, 2008).” On a day they studied quite intensively (14 August 2002), they report at 0600 EST, “the city was several degrees warmer than the suburbs, and up to 8°C warmer than rural areas within 100 km of the city.”

With respect to mitigation strategies, the 12 researchers determined “the most effective way to reduce urban air temperature is to maximize the amount of vegetation in the city with a combination of tree planting and green roofs.” Based on modeling studies of these approaches, they estimate this strategy could reduce simulated citywide urban air temperature by 0.4°C on average and 0.7°C at 1500 EST, and reductions of up to 1.1°C at 1500 EST could be expected in some Manhattan and Brooklyn neighborhoods, “primarily because there is more available area in which to plant trees and install vegetated roofs.” These findings reveal New York City already has experienced an urban-induced warming equivalent to what is predicted to occur by the end of the current century as a result of business-as-usual greenhouse gas emissions; planting additional vegetation throughout the city would likely moderate its thermal environment more than all the greenhouse-gas emissions reductions the world’s governments are ever likely to make.

Imhoff *et al.* (2010) note the urban heat island (UHI) phenomenon is “caused by a reduction in latent heat flux and an increase in sensible heat in urban areas as vegetated and evaporating soil surfaces are replaced by relatively impervious low-albedo paving and building materials,” and this replacement “creates a difference in temperature between urban and surrounding non-urban areas.” Most studies of this phenomenon have evaluated its magnitude by means of ground-based measurements of near-surface air temperature made at urban and rural weather stations, and they have found the urban-rural air temperature difference is expressed most strongly at night. Imhoff *et al.*, however, employed satellite-based measure-

ments of surface temperature, and they found this alternative measure of the UHI was most strongly expressed during the day.

The authors’ analysis included 38 of the most populous cities in the continental United States and their rural surroundings, where Imhoff *et al.* obtained land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on NASA’s Earth Observing System (EOS) satellites, which they used in a spatial analysis to assess UHI skin temperature amplitude and its relationship to development intensity, size, and ecological setting over three annual cycles (2003–2005), where urban impervious surface area (ISA) was obtained from the Landsat TM-based NLCD 2001 dataset.

The researchers report a city’s fractional ISA was a good linear predictor of LST for all cities in the continental United States in all biomes except deserts and xeric shrublands, and the fraction of ISA explains about 70 percent of the total variance in LST for all cities combined, with the highest correlations (90 percent) in the northeastern United States, where urban areas are often embedded in temperate broadleaf and mixed forests. They also determined the largest urban-rural LST differences for all biomes occurred during the summer around midday, and the greatest amplitudes were found for urban areas that displaced forests (6.5–9.0°C) followed by temperate grasslands (6.3°C) and tropical grasslands and savannas (5.0°C). Finally, they determined the contrast between urban cores and rural zones was typically “accentuated during the time when the vegetation is physiologically active, especially in forested lands,” and “the amplitude of the UHI is significantly diminished during the winter season when vegetation loses its leaves or is stressed by lower temperatures.” Imhoff *et al.* conclude “the use of ISA as an estimator of the extent and intensity of urbanization is more objective than population density based methods and can be consistently applied across large areas for inter-comparison of impacts on biophysical processes.”

Gonzalez *et al.* (2005) note “breezy cities on small tropical islands ... may not be exempt from the same local climate change effects and urban heat island effects seen in large continental cities,” describing research they conducted in and around San Juan, Puerto Rico. A NASA Learjet carrying the Airborne Thermal and Land Applications Sensor (ATLAS) that operates in visual and infrared wavebands flew several flight lines, both day and

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night, over the San Juan metropolitan area, the El Yunque National Forest east of San Juan, and other nearby areas, obtaining surface temperatures, while strategically placed ground instruments recorded local air temperatures. They found surface temperature differences between urbanized areas and limited vegetated areas were higher than 30°C during daytime, creating an urban heat island with “the peak of the high temperature dome exactly over the commercial area of downtown,” where noontime air temperatures were as much as 3°C greater than those of surrounding rural areas. In addition, the 11 researchers report, “a recent climatological analysis of the surface [air] temperature of the city has revealed that the local temperature has been increasing over the neighboring vegetated areas at a rate of 0.06°C per year for the past 30 years.”

Gonzalez *et al.* state “the urban heat island dominates the sea breeze effects in downtown areas,” and “trends similar to those reported in [their] article may be expected in the future as coastal cities become more populated.”

Velazquez-Lozada *et al.* (2006) evaluated the thermal impacts of historical land cover and land use (LCLU) changes in San Juan, Puerto Rico over the last four decades of the twentieth century by analyzing air temperatures measured at a height of approximately two meters above ground level within four different LCLU types (urban-coastal, rural-inland, rural-coastal, and urban-inland). They estimated what the strength of the urban heat island might be in the year 2050, based on anticipated LCLU changes and a model predicated on their data of the past 40 years. Their work revealed “the existence of an urban heat island in the tropical coastal city of San Juan, Puerto Rico that has been increasing at a rate of 0.06°C per year for the last 40 years.” They report predicted LCLU changes between now and 2050 will lead to an urban heat island effect “as high as 8°C for the year 2050.”

Noting a mass population migration from rural Mexico into medium- and large-sized cities took place throughout the second half of the twentieth century, Jáuregui (2005) examined the effect of this rapid urbanization on city air temperatures, analyzing the 1950–1990 minimum air temperature series of seven large cities with populations in excess of a million people and seven medium-sized cities with populations ranging from 125,000 to 700,000 people. Temperature trends were positive at all locations, ranging from 0.02°C per decade to 0.74°C per decade. Grouped by population, the average trend for

the seven large cities was 0.57°C per decade, and the average trend for the seven mid-sized cities was 0.37°C per decade. These results, Jáuregui writes, “suggest that the accelerated urbanization process in recent decades may have substantially contributed to the warming of the urban air observed in large cities in Mexico,” once again illustrating the magnitude of the urban heat island effect compared to the global warming of the past century, as well as the urban heat island’s dependence on the nature of the urban landscape. This further suggests it is next to impossible to adjust surface air temperature measurements made within an urban area to the degree of accuracy required to correctly quantify background or rural climate change, which may be an order of magnitude or two smaller than the perturbing effect of the city.

Garcia Cueto *et al.* (2009) used daily records of maximum and minimum temperature from six weather stations “in Mexicali City [Mexico] and its surroundings” covering the period 1950–2000, and “a climatic network of rural and urban weather stations in Mexicali and its valley and the Imperial Valley, California” over the “contemporary period (2000–2005),” to characterize the spatial and temporal development of the city’s urban heat island over the latter half of the twentieth century and the first five years of the twenty-first century. Mexicali City is located along the border of the United States at the northern end of Mexico’s Baja California. It is an urban settlement that had its beginnings in the first decade of the twentieth century, when it had an area of approximately 4 km²; by 1980 it covered a little more than 40 km², and by 2005 it extended over more than 140 km².

The researchers found Mexicali City “changed from being a cold island (1960–1980) to a heat island with a maximum intensity of 2.3°C in the year 2000, when it was compared with rural weather stations of Imperial, California,” concluding “the replacement of irrigated agricultural land by urban landscapes, anthropogenic activity and population growth, appear to be the major factors responsible for the observed changes.” From “more updated information (2000–2005),” they found “the greatest intensity of the urban heat island was in winter with a value of 5.7°C, and the lowest intensity in autumn with 5.0°C.”

These North American studies confirm the impact of population growth on the urban heat island effect is very real and can be very large, vastly overshadowing the effects of natural temperature change. As Oke (1973) demonstrated four decades ago, towns with as

few as a thousand inhabitants typically create a warming of the air within them that is more than twice as great as the increase in mean global air temperature believed to have occurred since the end of the Little Ice Age, and the urban heat islands of the great metropolises of the world create warmings that rival those that occur between full-fledged ice ages and interglacials.

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4.2.2.4 Rest of World

The previous two subsections examined the effects of urbanization on temperatures in Asia and North America. This section reviews studies examining this phenomenon in other parts of the world.

Bohm (1998) studied nine urban, suburban, and rural temperature records (three of each type, determined to be the best available on the basis of careful study from a total of 34 available records) to determine the evolving nature of the heat island of Vienna, Austria between 1951 and 1996, a 45-year period in which the city experienced zero population growth. Simultaneously, however, there was a 20 percent decrease in woodland and a 30 percent decrease in grassland within the city, as well as a doubling of the number of buildings; a tenfold increase in the number of cars; a 60 percent increase in street, pavement, and parking area; and a 2.5-fold increase in energy consumption. Bohm found the suburban stations exhibited city-induced temperature increases ranging from 0.11 to 0.21°C over the 45-year period of the study, while the urban stations experienced city-induced temperature increases ranging from zero, in the historic center of the city, to 0.6°C in the area of most intensive urban development.

Bohm writes, “the case study of Vienna illustrates the weakness inherent in studies which use only two stations to describe urban heat islands or use linear regression models to connect population directly to heat island intensity and trend.” Both of these procedures are typically used in making corrections for urban heat island effects in studies of global near-surface air temperature trends. More detailed analyses of urban development characteristics are needed to correct the global temperature record of the past century to account for these phenomena.

Bottyan *et al.* (2005) examined the influence of built-up areas on the near-surface air temperature field of Debrecen, Hungary, which sits on nearly flat terrain in the Great Hungarian Plain with a population

of 220,000. The researchers used mobile measurements made under different types of weather conditions between March 2002 and March 2003. The researchers found “the area of the mean maximum UHI [urban heat island] intensity of higher than 2°C is 76 times larger in the non-heating season than in the heating season (0.5% and 38% respectively),” and “the strongest developments of UHI occurring in the warmer and colder periods were 5.8°C and 4.9°C respectively.” They also state they “proved a strong linear relationship between the mean UHI intensity and the urban parameters studied, such as built-up ratio and its areal extensions, in both seasons.”

Hughes and Balling (1996) analyzed near-surface air temperature data from what they describe as “five very large metropolitan areas and 19 stations from non-urban locations” of South Africa for the period 1960–1990, comparing their results with those of Jones (1994) for the same time interval. The pair of scientists report the mean annual air temperature trend of the five large cities averaged 0.24°C per decade, and the mean warming rate of the 19 non-urban centers was a statistically insignificant 0.09°C per decade over the 1960–1990 period, compared to the overall warming rate of 0.31°C per decade derived by Jones for the entire country.

In addition, Hughes and Balling note, the mean rate-of-warming difference between their urban and non-urban sites was driven primarily by increases in daily minimum temperatures, which rose at a mean rate of 0.07°C per decade at the non-urban stations but an average rate of 0.34°C per decade at the five large cities. The “disparate trends in temperature” between the urban and non-urban stations “suggest that urbanization has influenced the Jones (1994) records for South Africa over the 1960–1990 period of apparent rapid warming,” and “half or more of this recent warming may be related to urban growth, and not to any widespread regional temperature increase.”

Torok *et al.* (2001) studied urban heat islands in several cities in Australia with populations ranging from approximately 1,000 to 3,000,000 people. They report the maximum urban-rural temperature differences of the Australian cities were found to scale linearly with the logarithms of their populations, and Torok *et al.* note the same was true for cities in Europe and North America. The heat islands of Australian cities were generally less than those of similar-size European cities (which were less than similar-size North American cities), and they increased at a slower rate with population growth than did European cities (which increased more slowly

than did cities in North America). The regression lines of all three continents essentially converged in the vicinity of a population of 1,000 people, however, where the mean maximum urban-rural temperature difference was approximately 2.2 ± 0.2 °C.

The four researchers note their experimental results “were sampled during atypical conditions which were suitable for maximum urban heat island genesis,” and therefore “they cannot be used to adjust long-term annual mean temperature records for urban influences.” Nevertheless, they say their results imply “climatological stations in large cities should preferably be excluded from studies into long-term climate change,” and “those in small towns should be located away from the town centers.”

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- width. Temperature histories derived from the first of these properties are considered to be more accurate than reconstructions based on tree-ring width, as the latter are falsely influenced by the productivity-enhancing effect of the rise in the air’s CO₂ content, which has dramatically increased tree-ring widths, particularly over the past 70 years. This tree-ring growth record has been falsely attributed to a dramatic increase in air temperature, when in reality Earth has experienced no net warming over this period.
- Cowling and Sykes (1999) note many methods of palaeoclimate reconstruction “are built upon the assumption that plant-climate interactions remain the same through time or that these interactions are independent of changes in atmospheric CO₂.” This assumption had been challenged nearly a dozen years earlier by Idso (1989a) and a few years later by Polley *et al.* (1993). Other scientists reached the same conclusion, resulting in a sufficient volume of published research on the topic to conduct a review of it. Cowling and Sykes conducted such a review and conclude “a growing number of physiological and palaeoecological studies indicate that plant-climate interactions are likely not the same through time because of sensitivity to atmospheric CO₂.” They explain “C₃-plant physiological research shows that the processes that determine growth optima in plants (photosynthesis, mitochondrial respiration, photorespiration) are all highly CO₂-dependent.” Moreover, “the ratio of carbon assimilation per unit transpiration (called water-use efficiency) is sensitive to changes in atmospheric CO₂ and “leaf gas-exchange experiments indicate that the response of plants to carbon-depleting environmental stresses are strengthened under low CO₂ relative to today.”

4.1.3 Potential Problems with Climate Proxies

In addition to the errors that can affect temperature records of the modern era, such as those associated with urbanization as discussed in the previous section, several potential inaccuracies can, if not properly accounted for, adversely influence proxy temperature records of the more distant past. This section highlights some of the problems that have been identified, starting with a discussion of tree-ring proxies, as the IPCC has heavily relied on such proxies in the past.

Two tree-ring characteristics have been used to reconstruct histories of past air temperature trends around the world: tree-ring *density* and tree-ring

These phenomena combine to produce dramatic increases in plant growth and water use efficiency with increases in the air’s CO₂ content. Such increases in vegetative vigor had been interpreted (to the date of their writing) almost exclusively not in terms of atmospheric CO₂ variations but in terms of changes in air temperature and/or precipitation. Therefore, all previous plant-based climate reconstructions for a period of time over which the air’s CO₂ content had experienced a significant change must have been in error to some degree unless they accounted for the growth-enhancing effects of the CO₂ increase, which none had yet done, except LaMarche *et al.* (1984) and Graybill and Idso (1993).

Many scientists (including the IPCC) had been using long-term tree-ring chronologies—specifically,

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Mann *et al.* (1998, 1999)—to create a climate history of Earth that exhibits dramatic late-twentieth century warming that was likely far too great. As Briffa (2000) explains, the recent high growth rates of the trees in these chronologies “provide major pieces of evidence being used to assemble a case for anomalous global warming, interpreted by many as evidence of anthropogenic activity.” However, he continues, “the empirically derived regression equations upon which our reconstructions are based may be compromised if the balance between photosynthesis and respiration is changed” by anything other than air temperature. And as Cowling and Sykes conclude, “implicit in the assumption that plant-climate relationships remain the same through time is the notion that temperature-plant interactions are independent of changes in atmospheric CO₂, which is not supported by physiological data.”

The flawed studies of Mann *et al.* fast became the centerpiece (Crowley, 2000; Mann, 2000) of the IPCC’s characterization of current climate, professing to show what they misguidedly concluded was an unusual and unprecedented rise in late-twentieth century temperatures, which they concluded to be largely the product of CO₂-induced global warming.

In another review paper conducted nearly a decade later, D’Arrigo *et al.* (2008) dissected this *divergence problem*, which they describe as “an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings,” assessing the possible causes and implications of the phenomenon.

The four researchers identified more than a dozen possible causes of the problem: moisture stress, non-linear or threshold responses to warming, local pollution, delayed snowmelt, changes in seasonality, differential responses to maximum and minimum temperatures, global dimming, methodological issues related to “end effects,” biases in instrumental target data, the modeling of such data, declining stratospheric ozone concentrations, increased UV-B radiation at ground level, and “an upward bias in surface thermometer temperature measurements in recent years related to heat island effects.”

D’Arrigo *et al.* note “reconstructions based on northern tree-ring data impacted by divergence cannot be used to directly compare past natural warm periods (notably, the Medieval Warm Period) with recent 20th century warming, making it more difficult to state unequivocally that the recent warming is unprecedented.” With respect to a resolution of the issue, they state their review “did not yield any

consistent pattern that could shed light on whether one possible cause of divergence might be more likely than others,” leading them to conclude “a combination of reasons may be involved that vary with location, species or other factors, and that clear identification of a sole cause for the divergence is probably unlikely.” Such findings suggest it is premature to claim, as the IPCC does, that recent warming is unprecedented over the past millennium or more, particularly on the basis of tree-ring width data.

In another paper examining the potential influence of atmospheric carbon dioxide on proxy records Gonzales *et al.* (2008) write, “there has been a growing awareness that past variations in CO₂ may have globally influenced plant physiology, vegetation composition, and vegetation structure (Idso, 1989b; Cowling, 1999; Cowling and Sykes, 1999; Wu *et al.*, 2007a,b).” They also note “this information has spurred a debate over the relative importance of CO₂ versus climate as drivers of Quaternary vegetation change.” Gonzales *et al.* compared simulated and pollen-inferred leaf area index (LAI) values with regional vegetation histories of northern and eastern North America “to assess both data and model accuracy and to examine the relative influences of CO₂ and climate on vegetation structure over the past 21,000 years.” They made use of BIOME4, “a biogeochemistry-biogeography equilibrium vegetation model (Kaplan, 2001)” that “was designed in part for paleo-vegetation applications, and has been widely used to simulate vegetation responses to late-Quaternary CO₂ and climates.” Concurrently, and “to provide paleo-climate scenarios for the BIOME4 simulations,” the three researchers “used surface temperature, precipitation and cloudiness values from a series of Hadley Centre Unified Model simulations.”

Gonzales *et al.* note theirs was the first study “to use both BIOME4 simulations and pollen-based reconstructions to develop detailed Quaternary LAI histories for North America,” and they report their “BIOME4 sensitivity experiments indicated that climate was the primary driver of late-Quaternary changes in LAI in northern and eastern North America, with CO₂ a secondary factor.” More importantly, Gonzales *et al.* observed their work “emphasizes the need for models to incorporate the effects of both CO₂ and climate on [the reconstruction of] late-Quaternary vegetation dynamics and structure.” Vegetation-based climate reconstructions must incorporate the biological effects of changes in

atmospheric CO₂ concentration, especially when attempting to compare late-twentieth century reconstructed temperatures with reconstructed temperatures of the Roman and Medieval Warm Periods and the Holocene Climatic Optimum. Until this deficiency is corrected, truly valid comparisons between these earlier times and the present cannot be made based on tree-ring width data.

Knapp and Soule (2008) examined recent radial growth increases in western juniper trees (*Juniperus occidentalis* var. *occidentalis* Hook.) based on their analysis of a master tree-ring chronology dating from AD 1000–2006, developed from 11 semi-arid sites in the interior U.S. Pacific Northwest that had experienced minimal anthropogenic influence other than that provided by the historical increase in the air's CO₂ content that is everywhere present.

They then used measured climate data for the period 1907–2006 to determine which climatic parameter tree radial growth was most responsive to: temperature, precipitation, or drought severity, as represented by the Palmer Drought Severity Index (PDSI) for the month of June. They found June PDSI to be the most important factor, explaining fully 54 percent of annual radial growth variability. When they added CO₂ as a second predictive factor, they found it “accounted for a 14% increase in explanatory power.” In addition, they report, “use of the PDSI-only regression model produced almost exclusively positive residuals since 1977,” but “the +CO₂ model has a greater balance of positive (53%) and negative residuals over the same period.” They conclude, “climatic reconstructions based on pre-1980 data would not be significantly influenced by rising CO₂ levels,” but reconstructions produced after that time would be.

During the period 1977–2006, which Knapp and Soule describe as being “unlike any other period during the last millennium,” the late-twentieth century/early-twenty-first century radial growth of the western juniper trees was 27 percent greater than the long-term (AD 1000–2006) average. That growth could not have been caused by any increase in air temperature, for they report “western juniper responds negatively to temperature, negating any linkages to regional warming.” Neither could the anomalous growth increase have been due to anomalous nitrogen fertilization, for the two researchers note “the eleven chronology sites do not fall under any of the criteria used to identify ecosystems significantly impacted by N-deposition,” citing the work of Fenn *et al.* (2003). They were left to conclude the growth increase was

likely due to the increase in the air's CO₂ content over the latter period.

Esper *et al.* (2005) weigh in on why there are differences among climate reconstructions and what it would take to reduce present uncertainties to gain a more complete and correct understanding of temperature changes over the past thousand years. The six scientists note we generally understand the shape of long-term climate fluctuations better than their amplitudes. For instance, nearly all 1,000-year temperature reconstructions capture the major climatic episodes of the Medieval Warm Period, Little Ice Age, and Current Warm Period, but for various reasons they exhibit differences in the degree of climatic warming or cooling experienced in the transitions between them, which for decadal means may amount to as much as 0.4 to 1.0°C. They suggest the discrepancies might be reduced by reducing the calibration uncertainty among the proxies, ensuring the accurate preservation and assessment of low-to-high frequency variation in proxy data, using appropriate frequency bands to best fit instrumental data, avoiding the use of regional tree-ring and other paleo records in which long-term trends (low-frequency variations) are not preserved, selecting instrumental data with which to compare proxy records to avoid incorrect alterations to the observational data that can result from homogeneity adjustments and methodological differences, and obtaining more proxy data that cover the full millennium and represent the same spatial domain as the instrumental target data (e.g., hemisphere).

In an important paper published in the peer-reviewed journal *Climatic Change*, Swiss scientists Jan Esper (of the Swiss Federal Research Institute) and David Frank (of the Oeschger Centre for Climate Change Research) took the Intergovernmental Panel on Climate Change (IPCC) to task for concluding in its *Fourth Assessment Report* (AR4) that, relative to modern times, there was “an increased heterogeneity of climate during medieval times about 1000 years ago.”

This finding, if true, would be of great significance to the ongoing debate over the cause of twentieth century global warming, because, Esper and Frank write, “heterogeneity alone is often used as a distinguishing attribute to contrast with present anthropogenic warming.” If the IPCC's contention is false, it would mean the warmth of the Current Warm Period is not materially different from that of the Medieval Warm Period, suggesting there is no need to invoke anything extraordinary (such as anthropogenic

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CO₂ emissions) as the cause of Earth's current warmth.

With mathematical procedures and statistical tests, Esper and Frank demonstrated the records reproduced in the AR4 “do not exhibit systematic changes in coherence, and thus cannot be used as evidence for long-term homogeneity changes.” And even if they could be thus used, they note “there is no increased spread of values during the MWP,” and the standard error of the component datasets “is actually largest during recent decades.” Consequently, the researchers conclude, their “quantification of proxy data coherence suggests that it was erroneous [for the IPCC] to conclude that the records displayed in AR4 are indicative of a heterogeneous climate during the MWP.” The IPCC's conclusion appears even more erroneous today in light of the hundreds of papers discussed in Section 4.2.2 that collectively demonstrate the homogeneity of a global MWP.

There are additional challenges in quantifying historical temperatures from other proxy methods. Correia and Safanda (1999) reviewed a set of 20 temperature logs derived from boreholes located at 14 sites in the small region of mainland Portugal in an attempt to reconstruct a five-century surface air temperature history for that part of the world, which proved to be a difficult task. Seven of the borehole temperature logs were too “noisy” to use, and six displayed evidence of groundwater perturbations and were thus not usable. Of the remaining seven logs, all depicted little temperature change over the first three centuries of record. Thereafter, four exhibited warming trends that began about 1800 and peaked around 1940, one showed a warming that peaked in the mid-1800s, another was constant across the entire five centuries, and one revealed cooling over the last century. These differences are surprising considering the relatively small distance separating the borehole locations. The two researchers conclude “the single inversions cannot be interpreted individually.”

Correia and Safanda next performed a joint analysis of the seven usable borehole records, obtaining a warming of 0.5–0.6°C since the second half of the eighteenth century, followed by a cooling of 0.2°C. They compared the joint borehole record with the surface air temperature record directly measured at a meteorological station in Lisbon, about 150–200 km to the northwest. From the beginning of the surface air temperature record in 1856 until 1949, the Lisbon data yielded a warming of 0.8°C, whereas the borehole record displayed a warming of only 0.3–0.4°C.

The two temperature histories could both be right, but they also could both be wrong. The Lisbon record, for example, could suffer from urban heat island-type problems, and the joint borehole record was obtained only after several individual records were rejected for various reasons and a number of simplifying assumptions were invoked in the analyses of the remaining records. The authors reluctantly recognize these problems, noting the issue was not yet resolved and much more work needed to be done to arrive at a satisfactory conclusion. This study demonstrates several common difficulties in deriving borehole temperature records.

Bodri and Cermak (2005) note temperature profiles derived from borehole records had been increasingly used to obtain proxy climate signals at various locations across the surface of Earth. They caution the techniques employed in reconstructing pre-observational (pre-instrumental era) mean temperatures from borehole data suffer from certain limitations, one of the major ones being the presence of underground fluids that can distort the true climatic signal (Lewis and Wang, 1992). Bodri and Cermak thus developed a corrective measure to account for vertical conductive and advective heat transport in a 1-D horizontally layered stratum—as opposed to the then-popular purely conductive approach—which they proceeded to apply to four borehole records drilled near Tachlovice in the Czech Republic.

The duo's analyses of the four borehole temperature logs revealed the conductive/advective approach was far superior to the purely conductive approach, explaining 83 to 95 percent of the temperature signal where the purely conductive model could explain no more than 27 to 58 percent. In addition, the purely conductive approach was found to underestimate the pre-observational mean temperature by 0.3 to 0.5°C. This underestimate produces a significant overestimate of the degree of warming experienced from the pre-observational period to the present. The two scientists also report both of the pre-observational mean temperature values for eighteenth-century Bohemia (the one derived from the conductive/advective approach and the one derived from the purely conductive approach) “exceed the annual temperatures characteristic for the 19th/20th centuries,” which “may indicate that the warming has still not achieved its earlier (late 18th century) level.”

Considering another type of possible proxy error, Darling *et al.* (2000) reported on their examination of the genetic variation in the small subunit ribosomal

RNA gene of three morphospecies of planktonic foraminifera from Arctic and Antarctic subpolar waters, which led to the discovery that foraminiferal morphospecies can consist of a complex of genetic types. They found each “species,” as these entities previously had been designated, was composed of three to five distinct genetic varieties that could be classified as individual species themselves. The morphological, chemical, and stable-isotope differences associated with the calcitic shells of the three morphospecies they studied are used extensively by palaeoceanographers for purposes of climate reconstruction, based on the assumption that each morphospecies represents a genetically continuous species with a single environmental/habitat preference. They write, “if this is not the case”—as indicated by their study and others—“stable-isotope and geochemical analyses of planktonic foraminiferal shells, and census-based transfer-function techniques derived from such pooled data, must include significant noise, if not error.” As more is learned about the diversity of these biotic climate indicators, it is likely certain additional palaeoclimatic histories will have to be revised.

Cohn and Lins (2005) analyzed statistical trend tests of hydroclimatological data such as discharge and air temperature in the presence of long-term persistence (LTP), in order to determine what LTP, if present, implied about the significance of observed trends. They determined “the presence of LTP in a stochastic process can induce a significant trend result when no trend is present, if an inappropriate trend test is used.” They also note, “given the LTP-like patterns we see in longer hydroclimatological records ... such as the periods of multidecadal drought that occurred during the past millennium and our planet’s geologic history of ice ages and sea level changes, it might be prudent to assume that hydroclimatological processes could possess LTP.” They add “nearly every assessment of trend significance in geophysical variables published during the past few decades has failed to account properly for long-term persistence.”

In discussing the implications of their work with respect to temperature data, Cohn and Lins note there is overwhelming evidence the planet has warmed during the past century. However, they ask, “could this warming be due to natural dynamics?” They state, “given what we know about the complexity, long-term persistence, and non-linearity of the climate system, it seems the answer might be yes.” Although reported temperature trends may be real, they note, those trends also may be insignificant. Cohn and Lins

say this leads to “a worrisome possibility”: that “natural climatic excursions may be much larger than we imagine, ... so large, perhaps, that they render insignificant the changes, human-induced or otherwise, observed during the past century.”

Another potential problem with paleoclimate proxies was identified by Loehle (2004), who used a pair of 3,000-year-long proxy climate records with minimal dating errors to characterize the pattern of climate change over the past three millennia in a paper that provides the necessary context for properly evaluating the cause or causes of twentieth century global warming.

The first of the two temperature series was the sea surface temperature (SST) record of the Sargasso Sea, derived by Keigwin (1996) from a study of the oxygen isotope ratios of foraminifera and other organisms contained in a sediment core retrieved from a deep-ocean drilling site on the Bermuda Rise. This record provided SST data for about every 67th year from 1125 BC to AD 1975. The second temperature series was the ground surface temperature record derived by Holmgren *et al.* (1999, 2001) from studies of color variations of stalagmites found in a cave in South Africa, which variations are caused by changes in the concentrations of humic materials entering the region’s groundwater that have been reliably correlated with regional near-surface air temperature.

Explaining why he used these two specific records and only these two records, Loehle writes, “most other long-term records have large dating errors, are based on tree rings, which are not reliable for this purpose (Broecker, 2001), or are too short for estimating long-term cyclic components of climate.” Also, in a repudiation of the approach employed by Mann *et al.* (1998, 1999) and Mann and Jones (2003), he states, “synthetic series consisting of hemispheric or global mean temperatures are not suitable for such an analysis because of the inconsistent timescales in the various data sets.” In addition, his testing indicates “when dating errors are present in a series, and several series are combined, the result is a smearing of the signal.”

Loehle reports “a comparison of the Sargasso and South Africa series shows some remarkable similarities of pattern, especially considering the distance separating the two locations,” and he states this fact “suggests that the climate signal reflects some global pattern rather than being a regional signal only.” He also notes a comparison of the mean record with the South Africa and Sargasso series from

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which it was derived “shows excellent agreement” and “the patterns match closely,” concluding, “this would not be the case if the two series were independent or random.”

Proceeding with his approach of fitting simple periodic models to the temperature data as functions of time, with no attempt to make the models functions of solar activity or any other physical variable, Loehle fit seven time-series models to the two temperature series and to the average of the two series, using no data from the twentieth century. In all seven cases, he reports good to excellent fits were obtained. As an example, the three-cycle model he fit to the averaged temperature series had a simple correlation of 0.58 and an 83 percent correspondence of peaks when evaluated by a moving window count.

Comparing the forward projections of the seven models through the twentieth century leads directly to the most significant conclusions of Loehle’s paper. He first notes six of the models “show a warming trend over the 20th century similar in timing and magnitude to the Northern Hemisphere instrumental series,” and “one of the models passes right through the 20th century data.” These results clearly suggest, in his words, “20th century warming trends are plausibly a continuation of past climate patterns” and, therefore, “anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes.”

Loehle’s analyses also reveal a long-term linear cooling trend of 0.25°C per thousand years since the peak of the interglacial warm period that occurred some 7,000 years ago, essentially identical to the mean value of this trend derived from seven prior assessments of its magnitude and five prior climate reconstructions. In addition, Loehle’s analyses reveal the existence of the Medieval Warm Period of AD 800–1200, which is shown to have been significantly warmer than the Current Warm Period Earth has experienced so far, as well as the existence of the Little Ice Age of AD 1500–1850, which is shown to have been the coldest period of the entire 3,000-year record.

As corroborating evidence for the global nature of these major warm and cold intervals, Loehle cites 16 peer-reviewed scientific journal articles that document the existence of the Medieval Warm Period in all parts of the world and 18 articles that document the worldwide occurrence of the Little Ice Age. In addition, both the Sargasso Sea and South African temperature records reveal the existence of a major temperature spike that began sometime in the early

1400s (though Loehle makes no mention of this feature in his paper). This abrupt warming pushed temperatures considerably above the peak warmth of the twentieth century before falling back to pre-spike levels in the mid-1500s, providing support for the similar finding of higher-than-current temperatures in that time interval by McIntyre and McKittrick (2003) in their reanalysis of the data Mann *et al.* used to create their controversial “hockey stick” temperature history, which gives no indication of the occurrence of this high-temperature regime.

The models developed by Loehle confirm the existence of three climate cycles previously identified by others. In his seventh model, for example, there is a 2,388-year cycle he describes as comparing “quite favorably to a cycle variously estimated as 2,200, 2,300, and 2,500 years (Denton and Karlen, 1973; Karlen and Kuylensstierna, 1996; Magny, 1993; Mayewski *et al.*, 1997).” In addition, there is a 490-year cycle that likely “corresponds to a 500-year cycle found previously (e.g. Li *et al.*, 1997; Magny, 1993; Mayewski *et al.*, 1997)” and a 228-year cycle that “approximates the 210-year cycle found by Damon and Jirikowic (1992).”

Loehle concludes, “solar forcing (and/or other natural cycles) is plausibly responsible for some portion of 20th century warming” or, as he indicates in his abstract, maybe even all of it.

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4.2 The Non-Uniqueness of Current Temperatures

The IPCC has long asserted CO₂-induced global warming accelerated significantly over the twentieth century and is unprecedented in the past millennium or more. However, as shown in the preceding section of this chapter, the temperature datasets upon which these claims are based are likely contaminated with errors of sufficient magnitude to render that assessment questionable at best.

The following section evaluates the correctness of the IPCC's claim. If temperatures of the past millennia—when atmospheric CO₂ concentrations were 30 percent lower than they are now—were as

warm as or warmer than the present, then it must be recognized there is nothing unusual or unnatural about the planet's current level of warmth. This would invalidate the IPCC's claims that “it is *extremely likely* that human activities have caused most of (at least 50%) the observed increase in global average temperatures since the 1950s” and “it is *virtually certain* that this warming is not due to internal variability alone” (Second Order Draft of AR5, dated October 5, 2012, p. 10-3).

Our review of the literature, highlighted in the subsections below, reveals many scientists have indeed presented evidence of *multiple* prior warm periods around the world. Much of this work focuses on a period of warmth about a thousand years ago, but some studies identify multiple periods throughout the Holocene when it was warmer than the present, at much lower atmospheric CO₂ concentrations. We begin with a discussion of current temperatures within the longer-term context of the past few interglacial climates.

4.2.1 The Warmth of Prior Interglacial Climates

Throughout Earth's geologic history, major ice ages have occurred repeatedly, with ten affecting the planet in the past one million years and another ten in the million or so years before that. Each persists for about 90,000 years, after which it is followed by an approximate 10,000-year interglacial.

Our understanding of climatic conditions during glacial–interglacial cycles is limited, but a constant flow of new studies is providing additional information about the topic. This growing body of knowledge provides a long historical baseline against which the current state of Earth's climate may be compared, enabling a better understanding of the significance of current climate trends and their causes.

Some scientists have claimed the ongoing rise in the air's CO₂ content made the decade of the 1990s the warmest period of the entire past millennium (Mann *et al.*, 1998, 1999). “Unprecedented” is the word proponents of this idea routinely use to describe the current temperature of the globe. However, when the mean temperature of the 1990s or 2000s is compared with the warmest temperatures of the four prior interglacials (for which we have high-quality reconstructed temperature records), the two decades are found to have been much cooler than *all* of these other periods.

Petit *et al.* (1999), for example, analyzed an ice

core recovered from the Russian Vostok drilling station in East Antarctica, from which they extracted a 420,000-year history of Earth's near-surface air temperature and atmospheric CO₂ concentration (see Figure 4.2.1.1). This record covered the current interglacial period, the Holocene, and the preceding four such climatic intervals. This record is important for what it reveals about the uniqueness or non-uniqueness of the Holocene: The current interglacial is by far the coldest of the five most recent such periods. The four interglacials that preceded the Holocene were, on average, more than 2°C warmer than the one in which we currently live. Also, atmospheric CO₂ concentrations during all four prior interglacials never rose above approximately 290 ppm, whereas the air's CO₂ concentration in mid-2013 stood at about 400 ppm. If there was anything unusual, unnatural, or unprecedented about late-twentieth century air temperatures, it is that they were so *low* in the presence of such *high* CO₂ concentrations.

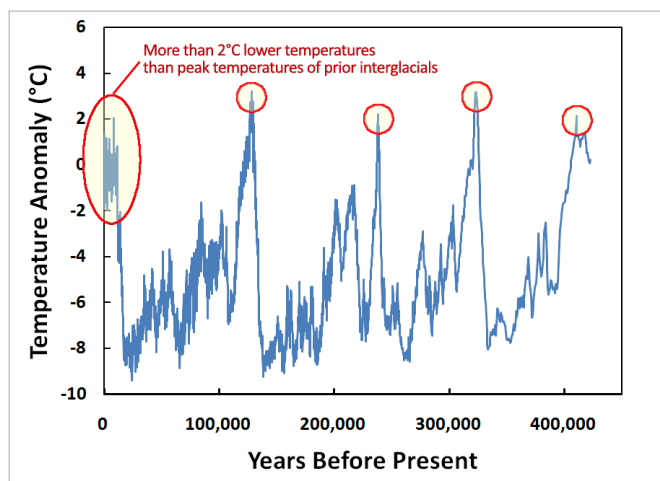


Figure 4.2.1.1. A 420,000-year history of Earth's near-surface air temperature extracted from an ice core recovered from the Russian Vostok drilling station in East Antarctica, revealing temperatures of the present are more than 2°C cooler than peak temperatures of all four prior interglacials. Adapted from 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..

Similar findings have been obtained from the Dome Fuji ice core, extracted from a site in an

entirely different sector of East Antarctica that is separated from the Vostok ice core site by 1,500 km (Watanabe *et al.*, 2003). Although of somewhat shorter duration, covering only the past three glacial-interglacial periods (marine stages 5.5, 7.5, and 9.3), this independent proxy temperature record also reveals the past three interglacials, in the words of Watanabe *et al.*, “were much warmer than the most recent 1,000 years (~4.5°C for stage 5.5 and up to 6°C for stage 9.3).”

This prior interglacial warmth is also evident in a 550,000-year sea surface temperature (SST) dataset derived by Herbert *et al.* (2001) from marine sediment cores obtained along the western coast of North America, from around 22°N latitude at the southern tip of the Baja Peninsula to around 42°N latitude off the coast of Oregon. According to this reconstructed SST dataset, the nine researchers who developed it write, “the previous interglacial (isotope stage 5e) 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 show SSTs for this region in the current interglacial have not reached the warm peaks witnessed in all four of the preceding interglacial periods, falling short by 1 to 4°C.

Thus, over the past half-million years and within the context of the most recent five full interglacials, it is clear the average near-surface air temperature of Earth during the 1990s was not unusually warm, but unusually *cool*, despite the 1990s' much greater atmospheric CO₂ content.

These observations suggest Earth's current temperature is not indicative of dangerous human interference with the planet's thermoregulatory system. The IPCC's claim of a human influence on today's climate is based solely on its contention that Earth's current temperature is uncommonly high (Crowley, 2000), when it clearly is not. Earth was significantly warmer than it is today in all of the preceding interglacials for which we have good temperature data, and it is highly implausible to attribute those high temperatures of the past to human influence or even natural increases in the air's CO₂ content, which during the four previous interglacials never rose above approximately 290 ppm.

The supposed causal relationship between Earth's atmospheric CO₂ concentration and global temperature has been further weakened by the work of Fischer *et al.* (1999), Indermuhle *et al.* (1999), and Stephens and Keeling (2000). Fischer *et al.* examined records of atmospheric CO₂ and air temperature

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derived from Antarctic ice cores across a quarter of a million years. Over this time span, the three most dramatic warming events were those associated with the terminations of the past three ice ages, and for each of these global warmings, Earth's air temperature rose well *before* any increase in atmospheric CO₂. The air's CO₂ content did not begin to rise until 400 to 1,000 years *after* the planet began to warm. Increases in the air's CO₂ content did not trigger these massive changes in climate.

In addition, during a 15,000-year period following one of the glacial terminations the air's CO₂ content was essentially constant but air temperatures dropped to values characteristic of glacial times. Also, just as increases in atmospheric CO₂ did not trigger any of the major global warmings that ended the past three ice ages, neither was the induction of the most recent ice age driven by a decrease in CO₂. And when the air's CO₂ content finally did begin to drop after the last ice age was fully established, air temperatures either remained fairly constant or rose, doing just the opposite of what climate models suggest should have happened if changes in atmospheric CO₂ drive changes in climate.

Indermuhle *et al.* (1999) determined the CO₂ content of the air gradually rose after the termination of the last great ice age, by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, in a time of slow but steady *decline* in global air temperature—again just the opposite of what would be expected if changes in atmospheric CO₂ affect climate in the way suggested by the popular CO₂-greenhouse effect theory.

Another problem for this theory arises from the work of Stephens and Keeling (2000), who in a study of the influence of Antarctic sea ice on glacial-interglacial CO₂ variations proposed a mechanism to explain the observed synchrony between Antarctic temperature and atmospheric CO₂ concentration during glacial-interglacial transitions. Their mechanism presumes temperature is the independent variable that alters sea ice extent, which then alters the sea-to-air CO₂ flux in the high-latitude region of the Southern Ocean and consequently changes the CO₂ content of the atmosphere. In their explanation for the gross correlation of CO₂ and air temperature over glacial-interglacial cycles, atmospheric CO₂ variations are clearly the result of temperature variations, not vice versa. (For a more in-depth discussion on the leads and lags of the historic temperature/CO₂ relationship, see Chapter 2.)

Ding *et al.* (1999) developed a high-resolution

record of climate changes over the past two glacial-interglacial cycles based on a study of grain sizes in soil cores removed from sections of the northwestern part of the Chinese Loess Plateau. The scientists detected the presence of large-amplitude millennial-scale climatic oscillations over both of the previous glacial periods, but very little such variation during the prior interglacial. Greater climatic stability during warmer interglacial periods also has been reported by Shemesh *et al.* (2001) and Alley (2000). Because interglacials appear to be more climatically stable than cooler glacial periods, we will likely not experience a significant increase in extreme weather events of the type routinely predicted by climate alarmists to accompany global warming, such as rapid climate changes of the type suggested to become more likely by Alley *et al.* (2002, 2003).

Across the long history of glacial-interglacial cycles, there is little doubt the atmosphere's CO₂ concentration is strongly correlated with its temperature, as has been demonstrated by numerous scientific studies (Petit *et al.*, 1999; Augustin *et al.*, 2004; Siegenthaler *et al.*, 2005). Nor is there any doubt changes in air temperature generally occur anywhere from 800 to 2,800 years *before* changes in the air's CO₂ content, as is demonstrated by even more studies (Fischer *et al.*, 1999; Monin *et al.*, 2001; Caillon *et al.*, 2003; Siegenthaler *et al.*, 2005). But the evidence shows carbon dioxide cannot be the primary cause of glacial-interglacial temperature changes, nor is it likely a significant amplifier of them.

Antarctic ice core data suggest the air's current CO₂ concentration is some 40 percent higher than it was at any other time in the past 650,000 years (Siegenthaler *et al.*, 2005), and its current methane concentration is approximately 130 percent higher (Spanhi *et al.*, 2005)—values some scientists have referred to as “geologically incredible.” If the IPCC and others were correct in attributing tremendous warming power to these two greenhouse gases, Earth should be experiencing incredibly high temperatures compared to those of prior interglacial periods. Yet this is not the case.

Greenland and Antarctica ice core data, in particular, suggest the mean recent temperature of the current interglacial, the Holocene, was not incredibly higher than temperatures reached during the past four interglacials, the earliest of which is believed to have been nearly identical to the Holocene in terms of Earth's orbit around the Sun. The mean recent temperature of the Holocene did not exceed temperatures reached during *any* of the four prior

interglacials, by even a fraction of a degree. On the contrary, the mean recent temperature of the Holocene was lower. The work of Petit *et al.* referred to earlier suggests the mean recent temperature of the Holocene was more than 2°C lower than the highest temperatures of the prior four interglacials, while another analysis of the subject (Sime *et al.*, 2009) suggests the “maximum interglacial temperatures over the past 340,000 years were between 6.0°C and 10.0°C above present-day values.”

The empirical observations cited above reveal a relationship opposite of what is expected if carbon dioxide and methane were the powerful greenhouse gases the IPCC claims them to be. Clearly, if there is anything at all that is unusual, unnatural, or unprecedented about Earth's current surface air temperature, it is that it is so *cold*.

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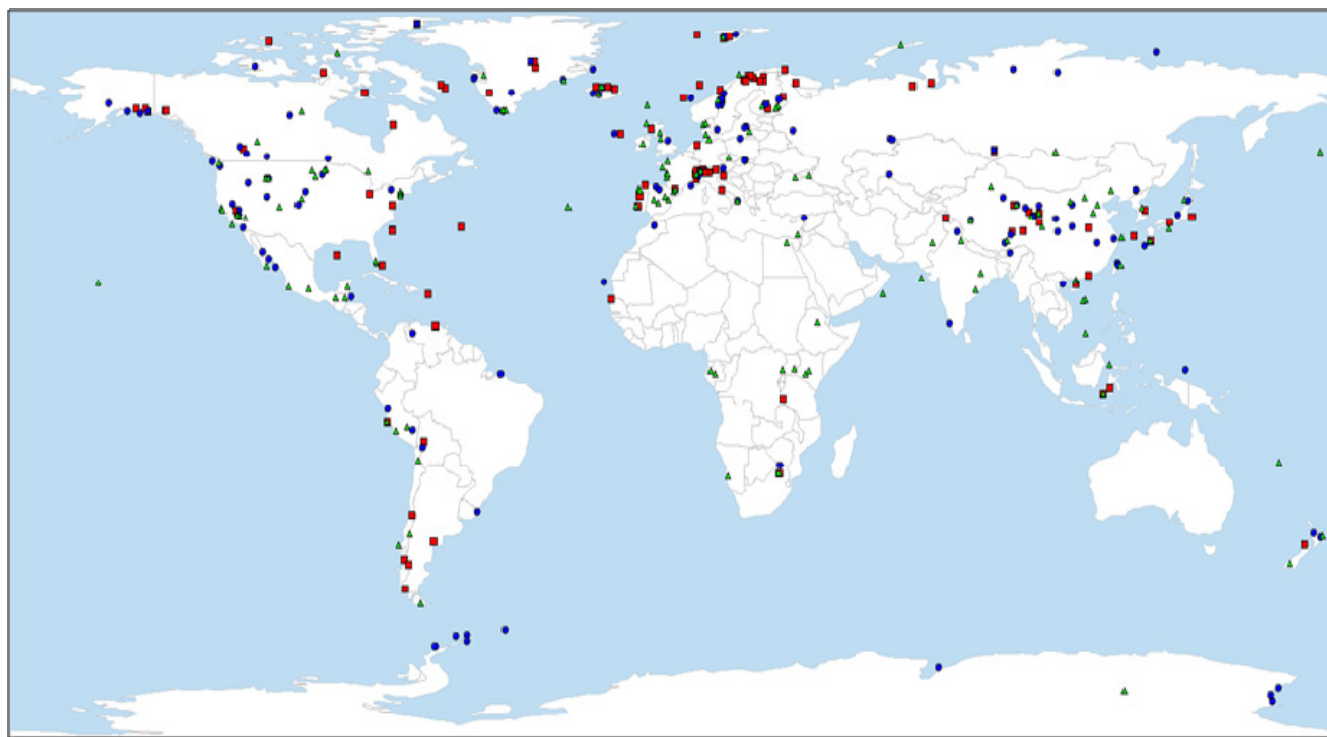


Figure 4.2.2.1. Plot of the locations of proxy climate studies for which (a) quantitative determinations of the temperature difference between the MWP and CWP can be made (red squares), (b) qualitative determinations of the temperature difference between the MWP and CWP can be made (blue circles), and (c) neither quantitative nor qualitative determinations can be made, with the studies simply indicating the Medieval Warm Period did indeed occur in the studied region (green triangles).

Spahni, R., Chappellaz, J., Stocker, T.F., Loulergue, L., Hausammann, G., Kawamura, K., Fluckiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V., and Jouzel, J. 2005. Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. *Science* **310**: 1317–1321.

Stephens, B.B. and Keeling, R.F. 2000. The influence of Antarctic sea ice on glacial-interglacial CO₂ variations. *Nature* **404**: 171–174.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H., and Yoshida, N. 2003. Homogeneous climate variability across East Antarctica over the past three glacial cycles. *Nature* **422**: 509–512.

4.2.2 A Global Medieval Warm Period

After initially acknowledging in its *First Assessment Report* the existence of a several-hundred-year global Medieval Warm Period (MWP) centered about a thousand years ago, during portions of which temperatures were often warmer than those of the present, the IPCC has since backtracked in succeeding reports. In its latest report (*Fifth*

Assessment), for example, the IPCC states:

In contrast to the late 20th century there is *high confidence* that the Medieval Climate Anomaly was not characterized by a pattern of higher temperatures that were consistent across seasons and regions (Second Order Draft of AR5, dated October 5, 2012, p. 5-4)

As demonstrated in this subsection and those that follow, there is in fact an enormous body of literature that clearly demonstrates the IPCC is wrong in its assessment of the MWP. The degree of warming and climatic influence during the MWP varied from region to region, and hence its consequences were manifested in a variety of ways. But that it occurred and was a global phenomenon is certain, and there are literally hundreds of peer-reviewed scientific articles that certify this truth.

In what is likely the largest synthesis of MWP research articles in the world, *CO₂ Science* (<http://www.co2science.org/data/mwp/mwpp.php>) has highlighted more than 350 peer-reviewed research

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papers documenting the global nature of this warm-temperature era.

Figure 4.2.2.1 illustrates the spatial distribution of the proxy climate studies analyzed by *CO₂ Science* according to three different categories. The first of these categories, denoted by the red squares, is comprised of studies where the scientists who conducted the work provided quantitative data that enable a determination of the degree by which the peak temperature of the MWP differed from the peak temperature of the Current Warm Period (CWP). The second category (blue circles) is comprised of studies where the scientists who conducted the work provided qualitative data that enable a determination of which of the two periods was warmer, but not by how much. The third category (green triangles) comprises studies where the MWP was evident in the study's data but the data did not provide a means by which the warmth of the MWP could be compared with that of the CWP. Such studies contradict the claim that the MWP, if it occurred at all, was only a regional phenomenon experienced by lands significantly influenced by the North Atlantic Ocean. This category also includes some studies based on data related to parameters other than temperature, such as precipitation. These studies help define the timeframe of the MWP, but they are not employed to infer anything about either its quantitative or qualitative thermal strength. Figure 4.2.2.1 reveals the truly global nature of this phenomenon.

With respect to how consistent the MWP was in time, of the 379 studies examined by *CO₂ Science*, 371 overlapped during the period 900–1200 AD. This number dips slightly to 365 if the time window is reduced to the period 1000–1200 AD, and to 337 if it is shortened further to the one hundred year period between 1000 and 1100 AD. A basic histogram of the timeframe (start year to end year) associated with the MWP of all the studies plotted in Figure 4.2.2.1 reveals the peak timeframe occurred around 1050 AD, within a more generalized 800 to 1300 AD warm era generally attributed to the MWP.

As to how warm it likely was during this period, Figure 4.2.2.2 presents a plot of the frequency distribution of all MWP-CWP temperature

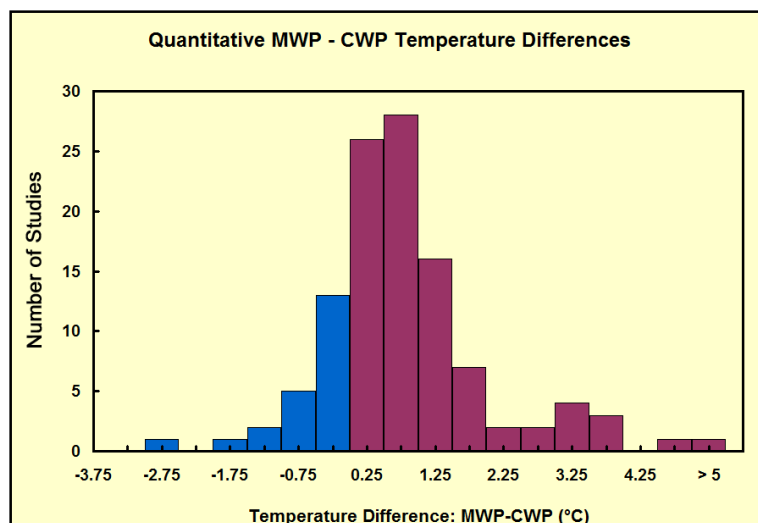


Figure 4.2.2.2. The distribution, in 0.5°C increments, of studies that allow the identification of the degree by which peak Medieval Warm Period temperatures either exceeded (positive values, red) or fell short of (negative values, blue) peak Current Warm Period temperatures.

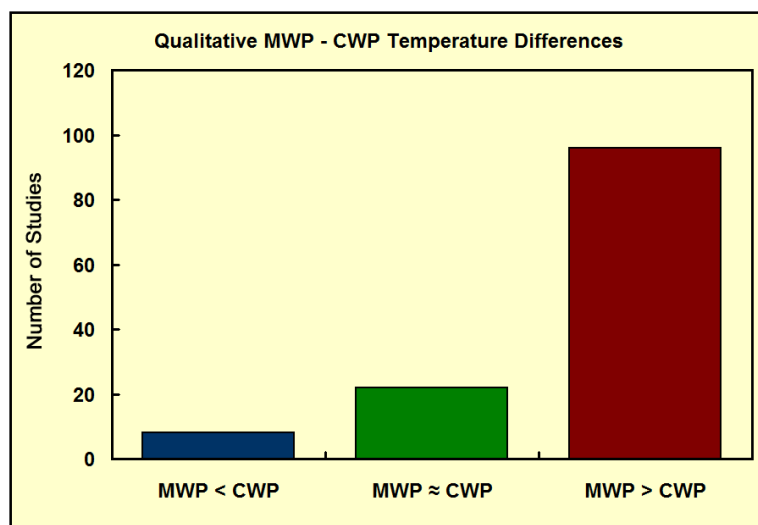


Figure 4.2.2.3. The distribution of studies that allow a qualitative determination of whether peak Medieval Warm Period temperatures were warmer than (red), equivalent to (green), or cooler than (blue) peak Current Warm Period temperatures.

differentials from all quantitative studies (red squares) shown in Figure 4.2.2.1. As Figure 4.2.2.2 reveals, some studies found the MWP to have been cooler than the CWP (blue columns), but the vast majority of the temperature differentials are positive (red columns), indicating the MWP was warmer than the CWP. The average of all such differentials is 0.91°C, while the median is 0.70°C.

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The greater warmth of the MWP can be generalized further by analyzing the qualitative studies in Figure 4.2.2.1, which is illustrated in Figure 4.2.2.3. Here, the numbers of studies in Figure 4.2.2.1 in which the MWP was warmer than, cooler than, or about the same as, the CWP are plotted, based on actual data presented by the authors of the original works. Again, a few studies found the MWP to have been cooler than the CWP, and a few found them to be of approximately the same warmth, but the majority of studies find the MWP to have been warmer than the CWP.

The existence of a global period of warmth in Earth's recent past comparable to that of the present indicates there is nothing unusual, unnatural, or unprecedented about the warmth of the post-1950 CWP. It is not surprising that there would be a significant warming of the globe at the conclusion of what was likely the coldest period of the entire Holocene (the Little Ice Age). Thus there is no compelling reason to believe twentieth century warming (which essentially ceased about 15 years ago) is a manmade phenomenon produced by the burning of coal, gas, and oil. The CWP is much more likely to be merely the most recent phase of the natural millennial-scale oscillation of Earth's climate that has been shown to operate throughout glacial and interglacial periods alike. And since the air's CO₂ concentration has risen by some 40 percent since the MWP, and Earth is no warmer now than it was then, there is no compelling reason to conclude any of Earth's current warmth is being caused by the increase in the atmosphere's CO₂ content.

We continue our analysis of the MWP by summarizing individual research papers on the subject, which together confirm the conclusions presented above.

Initial work from Lamb (1977, 1984, 1988) and Grove (1988) suggest Earth's average global temperature may have been warmer between the tenth and fourteenth centuries AD than it is today. The existence of this Medieval Warm Period initially was deduced from historical weather records and proxy climate data from England and Northern Europe. The warmer conditions of that era are known to have had a largely beneficial impact on Earth's plant and animal life. The environmental conditions of this time period have been determined to have been so favorable that it was often referred to as the Little Climatic Optimum (Imbrie and Imbrie, 1979; Dean, 1994; Petersen, 1994; Serre-Bachet, 1994; Villalba, 1994).

The degree of warming associated with the Medieval Warm Period varied from region to region, and its consequences were manifested in a variety of ways (Dean, 1994). In Europe, temperatures reached some of the warmest levels of the past 4,000 years, allowing enough grapes to be successfully grown in England to sustain an indigenous wine industry (Le Roy Ladurie, 1971). Horticulturists in China extended their cultivation of citrus trees and perennial herbs further and further northward, resulting in an expansion of their ranges that reached its maximum extent in the thirteenth century (De'ér, 1994). It has been estimated annual mean temperatures in the region must have been about 1.0 °C higher than at present, with extreme January minimum temperatures fully 3.5 °C warmer than they are today (De'ér, 1994).

In North America, tree-ring chronologies from the southern Canadian Rockies provide evidence for higher treelines and wider ring-widths between AD 950 and 1100, suggesting warmer temperatures and more favorable growing conditions (Luckman, 1994). Similar results were derived from tree-ring analyses of bristlecone pines in the White Mountains of California, where much greater growth was recorded in the eleventh and twelfth centuries (Leavitt, 1994). Analysis of ¹³C/¹²C ratios in the rings of these trees suggests soil moisture conditions were more favorable in this region during the Medieval Warm Period (Leavitt, 1994). Simultaneous increases in precipitation were found to have occurred in monsoonal locations of the United States desert southwest, where there are indications of increased lake levels from AD 700–1350 (Davis, 1994). Other data document vast glacial retreats during the MWP in parts of South America, Scandinavia, New Zealand, and Alaska (Grove and Switsur, 1994; Villalba, 1994), and ocean-bed cores suggest global sea surface temperatures were warmer then as well (Keigwin, 1996a, 1996b).

The Arctic ice pack substantially retreated during the MWP, allowing the settlement of both Iceland and Greenland, and alpine passes normally blocked with snow and ice became traversable, opening trade routes between Italy and Germany (Crowley and North, 1991). On the northern Colorado Plateau in America, the Anasazi Indian civilization reached its climax as warmer temperatures and better soil moisture conditions allowed them to farm a region twice as large as is currently possible (MacCracken *et al.*, 1990).

Huang and Pollack (1997) searched the large

database of terrestrial heat flow measurements compiled by the International Heat Flow Commission of the International Association of Seismology and Physics of the Earth's Interior for measurements suitable for reconstructing an average ground surface temperature history of the planet over the past 20,000 years. Working with a total of 6,144 qualifying sets of heat flow data obtained from every continent, they produced a global climate reconstruction independent of other proxy interpretations and of any preconceptions or biases as to the nature of the actual climate history. In this reconstruction of what they called "a global climate history from worldwide observations," the two researchers found strong evidence the MWP was indeed warmer than it had been during any prior portion of the twentieth century, by as much as 0.5°C.

Bard *et al.* (2000) describe some of the many different types of information used to reconstruct past solar variability, including "the envelope of the SSN [sunspot number] 11-year cycle (Reid, 1991), the length and decay rate of the solar cycle (Hoyt and Schatten, 1993), the structure and decay rate of individual sunspots (Hoyt and Schatten, 1993), the mean level of SSN (Hoyt and Schatten, 1993; Zhang *et al.*, 1994; Reid, 1997), the solar rotation and the solar diameter (Nesme-Ribes *et al.*, 1993), and the geomagnetic aa index (Cliver *et al.*, 1998)." They note, "Lean *et al.* (1995) proposed that the irradiance record could be divided into 2 superimposed components: an 11-year cycle based on the parameterization of sunspot darkening and facular brightening (Lean *et al.*, 1992), and a slowly-varying background derived separately from studies of Sun-like stars (Baliunas and Jastrow, 1990)."

In their own paper, Bard *et al.* take a different approach. Rather than directly characterizing some aspect of solar variability, certain consequences of that variability are assessed. They note magnetic fields of the solar wind deflect portions of the primary flux of charged cosmic particles in the vicinity of Earth, leading to reductions in the creation of cosmogenic nuclides in Earth's atmosphere, with the result that histories of the atmospheric concentrations of ^{14}C and ^{10}Be can be used as proxies for solar activity, as noted many years previously by Lal and Peters (1967).

Bard *et al.* first created a 1,200-year history of cosmogenic production in Earth's atmosphere from ^{10}Be measurements of South Pole ice (Raisbeck *et al.*, 1990) and the atmospheric $^{14}\text{C}/^{12}\text{C}$ record as measured in tree rings (Bard *et al.*, 1997). This record was then

converted to Total Solar Irradiance (TSI) values by "applying a linear scaling using the TSI values published previously for the Maunder Minimum," when cosmogenic production was 30 to 50 percent above the modern value. The end result of this approach was an extended TSI record suggesting "solar output was significantly reduced between 1450 and 1850 AD, but slightly higher or similar to the present value during a period centered around 1200 AD." They conclude "it could thus be argued that irradiance variations may have contributed to the so-called 'little ice age' and 'medieval warm period.'"

Also noting "the most direct mechanism for climate change would be a decrease or increase in the total amount of radiant energy reaching the Earth," Perry and Hsu (2000) developed a simple solar-luminosity model and used it to estimate total solar-output variations over the past 40,000 years. The model was derived by summing the amplitude of solar radiation variance for fundamental harmonics of the 11-year sunspot cycle throughout an entire 90,000-year glacial cycle, after which the model output was compared with geophysical, archaeological, and historical evidence of climate variation during the Holocene.

They determined model output was well correlated with the amount of carbon 14 (which is produced in the atmosphere by cosmic rays that are less abundant when the Sun is active and more abundant when it is less active) in well-dated tree rings going back to the time of the Medieval Warm Period (about AD 1100). This finding, they write, "supports the hypothesis that the Sun is varying its energy production in a manner that is consistent with the superposition of harmonic cycles of solar activity." The model output also was well correlated with the sea-level curve developed by Ters (1987). Present in both of these records over the entire expanse of the Holocene is a "little ice age"/"little warm period" cycle with a period of approximately 1,300 years. In addition, the climate changes implied by these records correlate well with major historical events. Specifically, the researchers note, "great civilizations appear to have prospered when the solar-output model shows an increase in the Sun's output," and such civilizations "appear to have declined when the modeled solar output declined."

Perry and Hsu note, "current global warming commonly is attributed to increased CO_2 concentrations in the atmosphere," but "geophysical, archaeological, and historical evidence is consistent with warming and cooling periods during the

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Holocene as indicated by the solar-output model.” They conclude the idea of “the modern temperature increase being caused solely by an increase in CO₂ concentrations appears questionable.”

Bond *et al.* (2001) consider what was responsible for the approximate 1,500-year cycle of global climate change in the North Atlantic Ocean that had been intensely studied and demonstrated to prevail throughout both glacial and interglacial periods alike. They studied ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (¹⁰Be) and Northern Hemispheric tree rings (¹⁴C).

Based on analyses of the deep-sea sediment cores that yielded the variable-with-depth amounts of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern and (using an accelerator mass spectrometer) date a number of recurring alternate periods of relative cold and warmth in the 12,000-year expanse of the Holocene. They determined the mean duration of the several complete climatic cycles was 1,340 years, and the cold and warm nodes of the most recent of these oscillations were “broadly correlative with the so called ‘Little Ice Age’ and ‘Medieval Warm Period.’”

The ten scientists linked these millennial-scale climate oscillations and their embedded centennial-scale oscillations with similar-scale oscillations in cosmogenic nuclide production, which are known to be driven by oscillations in the energy output of the Sun. Bond *et al.* report, “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.” They conclude, “a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic,” suggesting the cyclical climatic effects of the variable solar inferno are experienced throughout the world.

The international team of scientists verified that in spite of the contrary claims, the Little Ice Age and Medieval Warm Period were real, global, solar-induced, and but the latest examples of alternating intervals of relative cold and warmth stretching back in time through glacial and interglacial periods alike. Because these subjects are of such great significance to the debate over climate model-predicted consequences of anthropogenic CO₂ emissions, Bond *et al.* cite additional evidence in support of the implications of their work.

With respect to the global extent of the climatic impact of the solar radiation variations they detected,

they make explicit reference to confirmatory studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating the footprint of the solar impact on climate they documented extends “from polar to tropical latitudes.” They also note “the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence.” They further note their findings support previous suggestions that both the Little Ice Age and Medieval Warm Period “may have been partly or entirely linked to changes in solar irradiance.”

Bond *et al.* reiterate that the oscillations in drift-ice “persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system.” At two of their coring sites, they identified a series of cyclical variations that extended throughout all of the previous interglacials and were “strikingly similar to those of the Holocene.” Here, they also could have cited the work of Oppo *et al.* (1998), who observed similar climatic oscillations in a sediment core that covered the period from 340,000 to 500,000 years before present, and of Raymo *et al.* (1998), who pushed back the time of the cycles’ earliest known occurrence to well over one million years ago.

With respect to how the small changes in solar radiation inferred from cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth’s global climate, a question that had long plagued proponents of a solar-climate link, Bond *et al.* describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth’s surface, where they likely provoke changes in North Atlantic deep water formation that alter the global thermohaline circulation. They suggest the solar signals “may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint.”

Concluding their landmark paper, the ten scientists state the results of their study “demonstrate that the Earth’s climate system is highly sensitive to extremely weak perturbations in the Sun’s energy output,” noting their work “supports the presumption that solar variability will continue to influence climate in the future.”

Rigozo *et al.* (2001) reconstructed a history of sunspot numbers for the past 1,000 years “using a sum of sine waves derived from spectral analysis of the time series of sunspot number R_z for the period 1700–1999,” and from that record derived the strengths of a number of parameters related to solar variability over the past millennium.

The four researchers state, “the 1,000-year reconstructed sunspot number reproduces well the great maximums and minimums in solar activity that are identified in cosmonuclide variation records, and, more specifically, in the epochs of the Oort, Wolf, Sporer, Maunder, and Dalton Minimums, as well as the Medieval and Modern Maximums,” the latter of which they describe as “starting near 1900.” They report the mean sunspot number for the Wolf, Sporer, and Maunder Minimums was 1.36; for the Oort and Dalton Minimums it was 25.05; for the Medieval Maximum it was 53.00; and for the Modern Maximum it was 57.54. The mean sunspot number of the Oort and Dalton Minimums was thus 18.42 times greater than the average of the Wolf, Sporer, and Maunder Minimums, while the mean sunspot number of the Medieval Maximum was 38.97 times greater and the Modern Maximum 42.31 times greater. Similar strength ratios for the solar radio flux were 1.41, 1.89, and 1.97, respectively, and for the solar wind velocity the corresponding ratios were 1.05, 1.10, and 1.11, while for the southward component of the interplanetary magnetic field they were 1.70, 2.54, and 2.67.

Clearly, the sunspot number and solar variability parameters of the Medieval and Modern Maxima are dramatically greater than all other periods of the past thousand years. Thus, for entirely natural reasons, future temperatures may be higher than at any other time during the past millennium. Of course, other natural factors also affect Earth’s climate system and may mitigate that conclusion. In any event, the observations of Rigozo *et al.* and those of Bond *et al.* suggest there is no need for invoking variations in the air’s CO₂ content as the primary cause of mean global temperature variations during any period of the past thousand or more years.

Esper *et al.* (2002) employed a technique that allows accurate long-term climatic trends to be derived from individual tree-ring series of much shorter duration than the potential climatic oscillation being studied, and they applied this technique to more than 1,200 tree-ring series derived from 14 locations over the extratropical region of the Northern Hemisphere.

Two chronologies were thus developed: one from trees that exhibited weakly linear age trends and one from trees with nonlinear age trends. The results, they write, were “two nearly independent tree-ring chronologies covering the years 800–1990,” which were “very similar over the past ~1200 years.” These tree-ring histories were calibrated against Northern Hemispheric (0 to 90°N) mean annual instrumental temperatures from the period 1856–1980 to make them compatible with the temperature reconstructions of Mann *et al.* (1998, 1999), which were being cited by the IPCC and others as evidence current temperatures were greater than any previously experienced over the prior thousand years.

The biggest difference between the Esper *et al.* and Mann *et al.* temperature histories was the degree to which the coolness of the global Little Ice Age was expressed. It was much more evident in the record of Esper *et al.*, and its significantly lower temperatures made the Medieval Warm Period stand out more dramatically in their temperature reconstruction. Also, they note, “the warmest period covers the interval 950–1045, with the peak occurring around 990.” This finding, they write, “suggests that past comparisons of the Medieval Warm Period with the 20th-century warming back to the year 1000 have not included all of the Medieval Warm Period and, perhaps, not even its warmest interval.”

In a companion “perspective” paper, Briffa and Osborn (2002) acknowledge “the last millennium was much cooler than previously interpreted” and “an early period of warmth in the late 10th and early 11th centuries is more pronounced than in previous large-scale reconstructions.” The Esper *et al.* record makes it abundantly clear the peak warmth of the MWP was equivalent to the warmth of the late twentieth and early twenty-first centuries.

This reaffirms the point raised by Idso (1988): that there is no need to invoke CO₂-induced global warming as a cause of the planet’s recovery from the global chill of the Little Ice Age. “Since something other than atmospheric CO₂ variability was ... clearly responsible for bringing the planet into the Little Ice Age,” he writes, “something other than atmospheric CO₂ variability may just as well have brought the planet out of it.” That something else, as suggested by Esper *et al.*, was probably “the 1000- to 2000-year climate rhythm (1470 ± 500 years) in the North Atlantic, which may be related to solar-forced changes in thermohaline circulation,” as had been described by Bond *et al.* (2001).

Briffa and Osborn also note Esper *et al.*’s record

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clearly shows the warming of the twentieth century was simply “a continuation of a trend that began at the start of the 19th century.” In addition, the Esper *et al.* record indicates the Northern Hemisphere warmed in a consistent near-linear fashion over this 200-year period, contrary to the IPCC’s claim of unprecedented warming over only the last century. The new data did great damage to the assertion CO₂-enhanced greenhouse warming was responsible for the temperature increase that brought the planet out of the Little Ice Age, since the increase in the air’s CO₂ concentration over this period was highly nonlinear, rising by only 10 to 15 ppm over the nineteenth century but fully 70 to 75 ppm over the twentieth century, with no analogous increase in the latter period’s rate of warming.

Briffa and Osborn also state, “we need to know why it was once so warm and then so cool, before we can say whether 21st-century warming is likely to be nearer to the top or the bottom of the latest IPCC [predicted temperature] range.” We probably already know the answer to that question: The extremes of warmth and coolness to which they refer likely were caused by “solar-forced changes in thermohaline circulation,” as suggested by Esper *et al.* and described by Bond *et al.*

Krenke and Chernavskaya (2002) review the then-current state of knowledge about the Medieval Warm Period and Little Ice Age, throughout the world in general and in Russia in particular, based on written historical, glaciological, and hydrologic evidence and dendrological, archaeological, and palynological data. “Concerning the Medieval Warm Period (MWP),” they write, “it is currently known that, from the 9th century to, apparently, the mid-15th century, the climatic conditions were warmer than during most of the subsequent five centuries, including the early 20th century.” In some places it was warmer during the MWP than during the latter part of the twentieth century. For example, they note “the northern margin of boreal forests in Canada was shifted by 55 km [north] during the MWP, and the tree line in the Rocky Mountains in the southern United States and in the Krkonose Mountains was higher by 100–200 m than that observed at the present time.”

Regarding the temperature reconstructions of Mann *et al.* (1998, 1999), the two members of the Russian Academy of Sciences state “the temperature averaged over the 20th century was found to be the highest among all centennial means, although it remained within the errors of reconstructions for the

early millennium.” They further note, “one should keep in mind that the reconstructions of the early period were based nearly entirely on tree-ring data, which, because of the features of their interpretation, tend to underestimate low-frequency variations, so the temperatures of the Medieval Warm Period were possibly underestimated.” They provide further evidence for that conclusion, reporting, “the limits of cultivated land or receding glaciers have not yet exceeded the level characteristic of the early millennium.”

Specifically with respect to Russia, Krenke and Chernavskaya report large differences in several variables between the period of the Little Ice Age and the preceding Medieval Warm Period. With respect to the annual mean temperature of northern Eurasia, they report an MWP to LIA drop of 1.5°C. They also state, “the frequency of severe winters reported was increased from once in 33 years in the early period of time, which corresponds to the MWP, to once in 20 years in the LIA,” and they note “the abnormally severe winters [of the LIA] were associated with the spread of Arctic air masses over the entire Russian Plain.” Finally, they note the data they used to draw these conclusions were “not used in the reconstructions performed by Mann *et al.*,” which may explain why the Mann *et al.* temperature history of the past millennium does not reproduce the Little Ice Age nearly as well as does the more appropriately derived temperature history of Esper *et al.* (2002).

In contradiction of another of Mann *et al.*’s contentions, Krenke and Chernavskaya unequivocally state, based on the results of their study of the relevant scientific literature, “the Medieval Warm Period and the Little Ice Age existed globally.”

Soon and Baliunas (2003) also reviewed evidence pertaining to the climatic and environmental history of Earth over the past millennium. They found “the assemblage of local representations of climate establishes both the Little Ice Age and Medieval Warm Period as climatic anomalies with worldwide imprints, extending earlier results by Bryson *et al.* (1963), Lamb (1965), and numerous intervening research efforts.” In addition, they write, “across the world, many records reveal that the 20th century is probably not the warmest nor a uniquely extreme climatic period of the last millennium.”

Mayewski *et al.* (2004) examined 50 globally distributed paleoclimate records in search of evidence for what they called *rapid climate change* (RCC) over the Holocene. This terminology is not to be confused with the rapid climate changes typical of glacial

periods, but is used in the place of what the 16 researchers call the “more geographically or temporally restrictive terminology such as ‘Little Ice Age’ and ‘Medieval Warm Period.’” RCC events, as they also refer to them, are multi-century periods characterized by extremes of thermal and/or hydrological properties, rather than the much shorter periods when the changes that led to these situations took place.

Mayewski *et al.* say they identified six RCCs during the Holocene: 9,000–8000, 6,000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 cal yr BP, the last two of which are the “globally distributed” Medieval Warm Period and Little Ice Age, respectively. They note, “the short-lived 1200–1000 cal yr BP RCC event coincided with the drought-related collapse of Maya civilization and was accompanied by a loss of several million lives (Hodell *et al.*, 2001; Gill, 2000), while the collapse of Greenland’s Norse colonies at ~600 cal yr BP (Buckland *et al.*, 1995) coincides with a period of polar cooling.”

With respect to the causes of these and other Holocene RCCs, the international team of scientists concludes, “of all the potential climate forcing mechanisms, solar variability superimposed on long-term changes in insolation (Bond *et al.*, 2001; Denton and Karlen, 1973; Mayewski *et al.*, 1997; O’Brien *et al.*, 1995) seems to be the most likely important forcing mechanism.” They also declare “negligible forcing roles are played by CH₄ and CO₂,” and “changes in the concentrations of CO₂ and CH₄ appear to have been more the result than the cause of the RCCs.”

Braun *et al.* (2005) note many palaeoclimate records from Earth’s North Atlantic region depict a millennial-scale oscillation of climate, which during the last glacial period was highlighted by Dansgaard-Oeschger events that regularly recurred at approximately 1,470-year intervals, as reported by Rahmstorf (2003). Because of the consistency of their occurrence, it was generally believed these well-tuned periodic events were orchestrated by similarly paced solar activity, but no known solar process or orbital perturbation exhibited the periodicity of the Dansgaard-Oeschger events. Braun *et al.* (2005) performed an analysis that successfully explains this dichotomy.

Noting the periods of the DeVries-Suess and Gleissberg solar cycles (~210 and 87 years, respectively) are close to prime factors of 1,470 years, the team of eight German scientists write, “the

superposition of two such frequencies could result in variability that repeats with a 1,470-year period.” They proceed to show “an intermediate-complexity climate model with glacial climate conditions simulates rapid climate shifts similar to the Dansgaard-Oeschger events with a spacing of 1,470 years when forced by periodic freshwater input into the North Atlantic Ocean in cycles of ~86 and ~210 years.” The researchers state this exercise is “not aimed at suggesting a certain mechanism for solar influence on freshwater fluxes,” as they describe it, but merely to demonstrate “the glacial 1,470-year climate cycles could have been triggered by solar forcing despite the absence of a 1,470-year solar cycle.”

Braun *et al.*’s work suggests the similarly paced millennial-scale oscillation of climate that has reverberated throughout the Holocene, but with less perfect regularity, also is driven by the combined effect of the DeVries-Suess and Gleissberg solar cycles. The German scientists state the stimulus for their idea that “a multi-century climate cycle might be linked with century-scale solar variability comes from Holocene data,” citing the work of Bond *et al.* (2001), who had found “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,” and who concluded, “a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic.”

Bond *et al.* report the climatic oscillation’s most recent cold node and the warm node that preceded it were “broadly correlative with the so called ‘Little Ice Age’ and ‘Medieval Warm Period.’” Similarly, Rahmstorf states “the so-called ‘little ice age’ of the 16th–18th century may be the most recent cold phase of this cycle.” The logical extension of these observations is that the global warming of the past century or so, which propelled Earth out of the Little Ice Age and into the Current Warm Period, was a result of the most recent upswing in this continuing cycle of solar-induced climate change rather than any increase in the atmosphere’s CO₂ concentration.

Esper *et al.* (2005) sought to explain the significant differences among climatic reconstructions and what might be necessary to reduce uncertainties in order to gain a more complete and correct understanding of temperature changes over the past thousand years. According to the six scientists, for the most part we understand the *shape* of long-term climate fluctuations better than their *amplitudes*. For

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example, nearly all 1,000-year temperature reconstructions capture the major climatic episodes of the Medieval Warm Period, Little Ice Age, and Current Warm Period, but they exhibit differences in the degree of warming or cooling identified in the transitions between them, which for decadal means may amount to as much as 0.4 to 1.0°C.

Esper *et al.* suggest these discrepancies might be addressed by reducing the calibration uncertainty among the proxies, ensuring the accurate preservation and assessment of low-to-high frequency variation in proxy data, using appropriate frequency bands to best fit instrumental data, avoiding the use of regional tree-ring and other paleo-records in which long-term trends (low-frequency variations) are not preserved, selecting instrumental data with which to compare proxy records to avoid incorrect alterations to the observational data that can result from homogeneity adjustments and methodological differences, and obtaining more proxy data that cover the full millennium and represent the same spatial domain as the instrumental target data.

Esper *et al.* note knowledge of the correct amplitude of the major climatic episodes of the past millennium is “critical for predicting future trends.” If the amplitudes of the major historical climate episodes were as large as, or even greater than, the twentieth century global warming, there would be what they describe as a “redistribution of weight towards the role of natural factors in forcing temperature changes, thereby relatively devaluing the impact of anthropogenic emissions and affecting future predicted scenarios.” Efforts to reduce greenhouse gas emissions via national or international agreements “would be less effective than thought.”

Using data from 18 non-tree-ring-based 2,000-year proxy temperature series from around the world, Loehle (2007) smoothed the data in each series with a 30-year running mean, converted the results to anomalies by subtracting the mean of each series from each member of that series, and derived the final mean temperature anomaly history defined by the datasets by a simple averaging of the individual anomaly series. The results depict the Medieval Warm Period and Little Ice Age quite clearly, with the peak warmth of the MWP showing as approximately 0.3°C warmer than the peak warmth of the twentieth century. In a subsequent paper, Loehle and McCulloch (2008) obtained the results depicted in Figure 4.2.2.4. Although instrumental data are not strictly comparable to the reconstructed proxy data, the rise in global data from NASA GISS from 1935

(the end point of the figure) to 1992 (with data from 1978 to 2006) is 0.34°C, and “adding this rise to the 1935 reconstructed value, the MWP peak still remains 0.07°C above the end of the 20th-century values, though the difference is not significant.”

Based on data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland and using regional curve standardization (RCS) procedures, Helama *et al.* (2009) developed “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 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 as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture.” In addition, they write, “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 multi-centennial 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).”

Esper and Frank (2009) took the IPCC to task for concluding in its *Fourth Assessment Report* (AR4) that, relative to modern times, there was “an increased heterogeneity of climate during medieval times about 1000 years ago.” This finding, if true, would be of

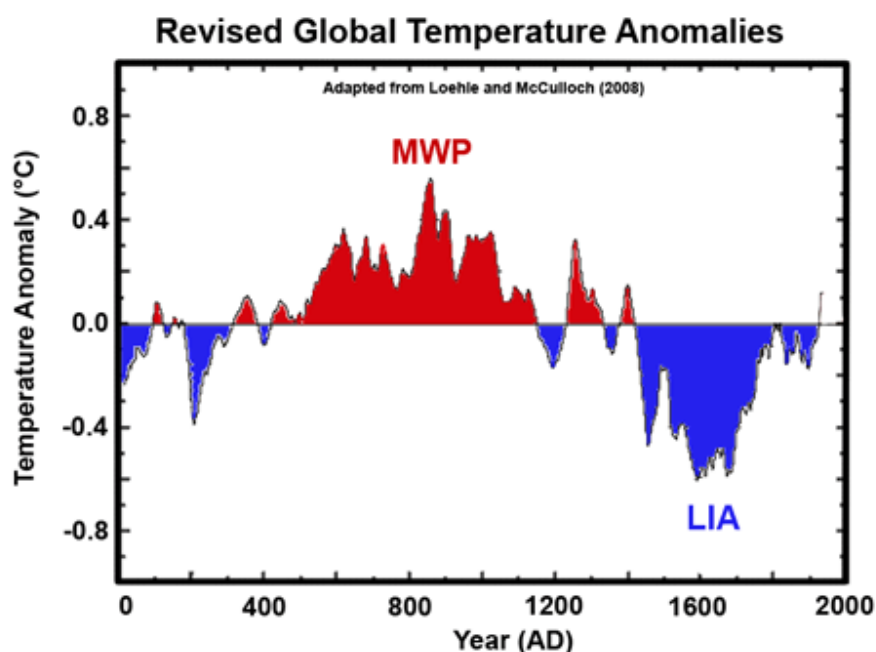


Figure 4.2.2.4. Mean relative temperature history of the globe. Adapted from Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* **19**: 93–100.

great significance to the ongoing debate over the cause of twentieth century global warming because, as Esper and Frank note, “heterogeneity alone is often used as a distinguishing attribute to contrast with present anthropogenic warming.” But if the IPCC’s contention is false, it would mean the warmth of the Current Warm Period is not materially different from that of the Medieval Warm Period, suggesting there is no need to invoke anthropogenic CO₂ emissions as the cause of Earth’s current warmth.

With mathematical procedures and statistical tests, Esper and Frank demonstrate the records reproduced in the AR4 “do not exhibit systematic changes in coherence, and thus cannot be used as evidence for long-term homogeneity changes.” They also note “there is no increased spread of values during the MWP,” and the standard error of the component datasets “is actually largest during recent decades.” Consequently, the two researchers conclude their “quantification of proxy data coherence suggests that it was erroneous [for the IPCC] to conclude the records displayed in AR4 are indicative of a heterogeneous climate during the MWP.”

The studies cited in this section clearly establish the verity of a global Medieval Warm Period. Hundreds of additional papers are cited in Sections 4.2.3 and 4.2.4.

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4.2.3 Prior Warm Periods in the Northern Hemisphere

Citing the work of Mann *et al.* (1998, 1999), the IPCC concluded in its *Fourth Assessment Report* that late twentieth century warming was unprecedented over the past millennium, a conclusion that remains intact in the IPCC's most recent report:

For average annual Northern Hemisphere temperatures, there is *medium confidence* that 1981–2010 CE was the warmest 30-year period of the last 1300 years and it is *very likely* that it was the warmest of the last 800 years (Second Order Draft of AR5, dated October 5, 2012, p 5–4)

As shown in this subsection, the IPCC is clearly ignoring the findings of several research teams who have presented results that counter their claims.

The Medieval Warm Period and subsequent Little Ice Age, which followed the Roman Warm Period and the Dark Ages Cold Period (McDermott *et al.*, 2001), were long considered classic examples of the warm and cold phases of a millennial-scale climate oscillation that has reverberated throughout glacial and interglacial periods (Oppo *et al.*, 1998; McManus *et al.*, 1999) as well as across the early Pleistocene (Raymo *et al.*, 1998).

In addition to their intrinsic historical value, the last of these alternating warm and cold periods are of particular relevance to the global warming debate. If there truly was a period near the beginning of the past millennium when temperatures were as warm as they are presently, but when the atmosphere's CO₂ concentration was only about 40 percent of today's level (280 ppm vs. 400 ppm), and if that period was followed by a several-centuries-long cold period with essentially no decline in the air's CO₂ content, there would be little basis for invoking the twentieth century increase in atmospheric CO₂ concentration as a reason for the planet's return to the warmth it had experienced a millennium earlier, as Idso (1988) argued a quarter-century ago and Broecker (1999) noted a decade later.

A pair of papers published by Mann *et al.* (1998, 1999) near the turn of the twenty-first century presented an interpretation of Earth's climatic history vastly different from what previously had been accepted by even the IPCC (Houghton *et al.*, 1990), which up to at least 1995 had depicted the existence of both the Medieval Warm Period and the Little Ice Age. The new history, derived from select proxy temperature records, showed, in the words of Esper *et al.* (2002), “an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time,” which is now routinely described by the IPCC as “the warmest period of the past millennium.” A few years later, the work of Esper *et al.* (2002) reaffirmed the earlier understanding of these unique climatic periods.

Esper *et al.* employed an analysis technique that allowed long-term climate trends to be derived from individual tree-ring series of much shorter duration than the potential climatic oscillation being studied, and they applied this technique to more than 1,200 tree-ring series derived from 14 locations over the extratropical region of the Northern Hemisphere. Two

separate chronologies were developed: one from trees that exhibited weakly linear age trends and one from trees with nonlinear age trends. The outcome, they write, was “two nearly independent tree-ring chronologies covering the years 800–1990,” which were “very similar over the past ~1200 years.” These tree-ring histories were calibrated against Northern Hemispheric (0 to 90°N) mean annual instrumental temperatures from the period 1856–1980 to make them compatible with the temperature reconstructions of Mann *et al.*

The biggest difference between the Esper *et al.* and Mann *et al.* temperature histories is the degree to which the coolness of the Little Ice Age is expressed. The Little Ice Age is much more evident in the record of Esper *et al.*, and its significantly lower temperatures make the Medieval Warm Period stand out more dramatically. Esper *et al.* note, “the warmest period covers the interval 950–1045, with the peak occurring around 990.” This finding, they write, “suggests that past comparisons of the Medieval Warm Period with the 20th-century warming back to the year 1000 have not included all of the Medieval Warm Period and, perhaps, not even its warmest interval.”

In a companion “perspective” paper, Briffa and Osborn (2002) acknowledge the last millennium “was much cooler than previously interpreted” and “an early period of warmth in the late 10th and early 11th centuries is more pronounced than in previous large-scale reconstructions.”

Esper *et al.*’s work reaffirms the point raised by Idso (1988): There is no need to invoke CO₂-induced global warming as a cause of the planet’s recovery from the global chill of the Little Ice Age. “Since something other than atmospheric CO₂ variability was ... clearly responsible for bringing the planet into the Little Ice Age,” he notes, “something other than atmospheric CO₂ variability may just as well have brought the planet out of it.” That something else, as suggested by Esper *et al.*, is probably “the 1000- to 2000-year climate rhythm (1470 ± 500 years) in the North Atlantic, which may be related to solar-forced changes in thermohaline circulation” as described by Bond *et al.* (2001).

Briffa and Osborn also note Esper *et al.*’s record clearly shows the warming of the twentieth century was “a continuation of a trend that began at the start of the 19th century.” In addition, the Esper *et al.* record indicates the Northern Hemisphere warmed in a consistent near-linear fashion over this 200-year period, contrary to the claim of unprecedented

warming over only the last century.

Briffa and Osborn conclude, “we need to know why it was once so warm and then so cool, before we can say whether 21st-century warming is likely to be nearer to the top or the bottom of the latest IPCC [predicted temperature] range.” The answer to this question is already known: The extremes of warmth and coolness to which Briffa and Osborn refer were likely caused by “solar-forced changes in thermohaline circulation,” as suggested by Esper *et al.* and described by Bond *et al.* It has become increasingly clear these significant climatic changes were not caused by changes in the air’s CO₂ content.

Briffa *et al.* (2002) worked with a network of high-latitude and high-elevation tree-ring chronologies obtained from 387 conifer sites that circled the extra-tropical Northern Hemisphere, comprised of almost 10,000 individual tree cores with chronologies ranging in length from 85 to more than 600 years, to reconstruct a “near-hemispheric scale” April-to-September temperature history. Based on the trees’ maximum latewood density, this temperature reconstruction exhibits a strong, spatially coherent response to decadal-scale temperature variability, but because of the particular standardization procedure they employed, Briffa *et al.* state their reconstruction was “likely to remove the century to multicentury timescale power.” The following discussion is limited to a consideration of what their work implied about the warming of the Northern Hemisphere in only the late twentieth century.

The year of coldest growing-season temperature in Briffa *et al.*’s reconstruction was 1912, after which temperatures rose in zigzag fashion to about 1930, whereupon they flattened out until approximately 1945, after which they declined in zigzag fashion until sometime in the late 1970s, when they began to fluctuate about a well-defined mean that persisted to the end of the century. At the dawning of the new millennium, Briffa *et al.*’s proxy temperatures were considerably below the peak warmth of the 1930s and early 1940s, in striking contrast to the instrumental temperature record, which soared to new heights in the 1980s and 1990s to achieve the century’s highest values, which were several tenths of a degree Centigrade greater than the temperatures derived from the 10,000 trees’ maximum latewood density data. Mann *et al.* (1998, 1999) used instrumental temperatures in lieu of proxy temperatures over the latter part of the century to arrive at what they called the “unprecedented” warming of its last two decades.

Is it appropriate, as Mann *et al.* did, to “switch

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horses” and compare two different things—early-century *proxy* temperatures and late-century *instrumental* temperatures—to conclude the twentieth century experienced unprecedented warming over its final two decades? Or is it more appropriate to finish the comparison with the parameter with which you began, which leads to the conclusion that the end of the century was likely no warmer than it was in the 1930s and early 1940s?

Briffa *et al.* approached this predicament by first acknowledging the existence of the problem, which they describe as “a deviation between reconstructed and observed temperature during the most recent three or four decades,” noting the deviation increases with time, “particularly since about 1970 (although perhaps starting as early as 1935).” They admit they could not find a “substantiated explanation for it,” so they *assumed* the deviation “is likely to be a response to some kind of recent anthropogenic forcing.” And they also assumed the anthropogenic forcing had perturbed the *proxy* temperature record.

A much less convoluted course of action would have been to assume the anthropogenic forcing had perturbed the *instrumental* temperature record. There is, after all, a well-known and “substantiated explanation” for this point of view: that Earth’s increasing population has been increasing the strength of urban heat island and altered land-use effects nearly everywhere on the land surface of the planet, and sufficiently accurate adjustments to the instrumental temperature record for these phenomena had not yet been made throughout the regions investigated by Briffa *et al.*

Since 1970, for example, the world’s population had grown by approximately 64 percent, and since 1935, when the first signs of the deviation between the proxy and instrumental temperature records began to occur, the number of people on the planet had grown by more than 200 percent. With urban heat islands routinely raising city air temperatures several degrees Centigrade above the temperatures of their surrounding rural environs, and since towns with as few as a thousand inhabitants have been shown to possess heat islands of two degrees Centigrade or more (Oke, 1973; Torok *et al.*, 2001), it is clear population growth easily could have produced a gradually increasing elevation of the instrumental temperature record (typically developed from temperatures measured in cities and towns) relative to the basically rural temperature record typical of the locations where the tree-ring chronologies studied by Briffa *et al.* were obtained. This phenomenon easily

could account for the several tenths of a degree Centigrade by which instrumental and proxy temperature records differed at the end of the twentieth century.

There are several other reasons for accepting this analysis of the diverging-temperature-records dilemma instead of yielding to the six scientists’ default assumption. Briffa *et al.* could identify no credible mechanism for producing the problem they imagined to exist with the late twentieth century proxy temperatures, so they gave up, saying “to search for an explanation is beyond the scope of this paper.” They could not produce an explanation that would apply to the entire Northern Hemisphere and be readily comprehended by most reasonable people as having at least the potential to be correct.

One also wonders what kind of “recent anthropogenic forcing” could have had such a substantial negative effect on tree growth and wood density over the latter part of the twentieth century. Atmospheric pollution is one possibility, especially rising ozone (O₃) concentrations. However, in numerous studies of the net effect of elevated O₃ and CO₂ acting together on trees, the positive effects of elevated CO₂ often have been found to compensate, and sometimes even more than compensate, for the negative effects of elevated O₃ (Grams *et al.*, 1999; Noormets *et al.*, 2001; Liu *et al.*, 2004). The positive effects of elevated CO₂ also have been found to compensate for the negative effects of elevated sulfur dioxide concentrations (Deepak and Agrawal, 2001; Izrael *et al.* (2002); Agrawal and Deepak, 2003). Rising atmospheric CO₂ concentrations are known to significantly stimulate the growth rates of essentially all woody plants and increase the density of the wood produced by trees (Kilpelainen *et al.*, 2003; Kostianinen *et al.*, 2004).

In light of these observations, it is highly unlikely human activity is reducing the growth and wood density of Earth’s trees, especially those growing in the relatively remote locations used to develop the data analyzed by Briffa *et al.* It is far more likely the divergence of the instrumental and proxy temperature records analyzed by Briffa *et al.* is caused by an anthropogenic effect on the *instrumental* record than on proxy record. Thus the hockey stick temperature record of Mann *et al.* (1998, 1999) would appear to be patently erroneous over the last few decades of the twentieth century, substituting as it does the increasingly inflated instrumental temperature record for the more correct and stable proxy temperature record.

Esper and a group of five new coauthors—Esper *et al.* (2003)—processed several long juniper tree-ring-width chronologies for the Alai Range of the western Tien Shan in Kirghizia in way that preserved 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 maintain 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 (actually removes) such long-term trends.

Carried back in time a full thousand years, the SPL chronologies depicted significant interdecadal variations but no longer-term trends. The LTM and RCS chronologies, by contrast, showed long-term decreasing trends until about AD 1600, broad minima from 1600 to 1800, and long-term increasing trends from about 1800. Esper *et al.* write, “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 Hemispheric extratropic temperature history of Esper *et al.* (2002), which is vastly different from the hockey stick temperature history of Mann *et al.* (1998, 1999) and Mann and Jones (2003), in that it depicts the existence of both the Little Ice Age and the preceding Medieval Warm Period, which are nowhere to be found in the Mann reconstructions. The new result—especially the LTM chronology, which has a much smaller variance than the RCS chronology—depicts several periods in the first half of the past millennium that were warmer than any part of the past 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 (McIntyre and McKittrick, 2003; Loehle, 2004).

Briffa *et al.* (2004) reviewed several analyses of maximum latewood density data derived from a widespread network of tree-ring chronologies that spanned three to six centuries and were obtained from nearly 400 different locations. For the land area of the globe poleward of 20°N latitude, their work reveals the warmest period of the past six centuries occurred in the 1930s and early 1940s. Thereafter, the mean temperature of the region declined dramatically. It recovered somewhat over the last two decades of the

twentieth century, but its final value was still below the mean value of the 1400s and portions of the 1500s.

Averaged over all land area poleward of 50°N latitude, there was a marked divergence of reconstructed and instrumental temperatures subsequent to 1960, with measured temperatures rising and reconstructed temperatures falling, such that by the end of the record there was an approximate 1.5°C difference between them. The three researchers attempted to relate this large temperature differential to a hypothesized decrease in tree growth caused by a hypothesized increase in ultraviolet radiation, which they hypothesized to have been caused by declining stratospheric ozone concentrations over this period. The results of this effort, however, proved “equivocal,” as they describe them, leaving considerable room for urban heat island effects and other land-cover changes to have been the principal causes of the observed temperature divergence, as suggested by Gallo *et al.* (1996, 1999) and Kalnay and Cai (2003). Briffa *et al.* state these unsettled questions prevented them “from claiming unprecedented hemispheric warming during recent decades on the basis of these tree-ring density data alone.” Their analyses also fail to provide convincing evidence for the validity of the Northern Hemispheric temperature reconstructions of Mann *et al.* (1998, 1999) and thus fail to support the IPCC’s contention that the warming of high northern latitudes should be significantly greater than that of the rest of the Northern Hemisphere.

While studying lichens of the subspecies *Rhizocarpon geographicum* found on avalanche boulder tongues in the eastern part of the Massif des Ecrins of the French Alps, Jomelli and Pech (2004) made an important discovery: High-altitude avalanche activity during the Little Ice Age reached an early maximum prior to 1650, after which it decreased until about 1730, whereupon it increased once again, reaching what was likely its greatest maximum about 1830. The two researchers note “a greater quantity of snow mobilized by avalanches during the LIA can be supported by the fact that the two periods, AD 1600–1650 and 1830, during which the run-out distances [of the avalanches] were maximum at high elevation sites, have corresponded overall to the periods of maximum glacial advances for these last 500 years (Le Roy Ladurie, 1983; Reynaud, 2001).” In addition, they report “since 1850 most French Alpine glaciers have decreased” and “the mass balance of these glaciers is directly correlated with summer

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temperature and spring precipitation (Vincent and Vallon, 1997; Vincent, 2001, 2002)."

These findings and those of other scientists cited by Jomelli and Pech suggest the beginning of the end of the Little Ice Age started somewhere in the early to mid-1800s. Moore *et al.* (2002) determined a similar start-time for the demise of the Little Ice Age from temperature data gathered on Mount Logan in Canada, and further support for this conclusion has come from studies of still other parameters, including deep soil temperatures (Gonzalez-Rouco *et al.*, 2003), deep ocean temperatures (Lindzen, 2002), and dates of ice break-up of lakes and rivers (Yoo and D'Odorico, 2002). This is also when the temperature record of Esper *et al.* (2002) indicates the Northern Hemisphere began its nearly-linear-with-time recovery from the depths of the Little Ice Age. As Briffa and Osborn (2002) describe it, Esper *et al.*'s record clearly shows the warming of the twentieth century was actually "a continuation of a trend that began at the start of the 19th century."

The temperature history of Mann *et al.* (1998, 1999) suggests post-Little Ice Age warming did not begin until about 1910. They appear to have missed as much as half the warming experienced by Earth in recovering from what was likely the coldest part of the Little Ice Age. An even greater part of the total warming occurred before the air's CO₂ concentration began increasing in earnest (approximately 1930, close to the time when warming peaked in the United States and many other parts of the world). Thus the lion's share of the warming of the past nearly two centuries must owe its existence to something other than rising atmospheric CO₂ concentrations.

Gray *et al.* (2004) write, "natural, low-frequency variations" in near-surface air temperature may "mask or amplify secular trends in the climate system." Hence, it is important—even necessary—to study such phenomena in order to determine the cause or causes of recent climate change. Gray *et al.* developed a reconstruction of the leading mode of low-frequency North Atlantic (0–70°N) sea surface temperature variability—i.e., the Atlantic Multidecadal Oscillation (AMO)—for the period AD 1567–1990, based on tree-ring records from regions known to border on strong centers of AMO variability: eastern North America, Europe, Scandinavia, and the Middle East.

In terms of both duration and magnitude, the four researchers found the "AMO variability observed in late-19th and 20th century instrumental records is typical of North Atlantic multidecadal behavior over

longer periods." They also observed a new warming phase had begun in the mid-1990s and the most intense warm phase of the AMO record occurred between 1580 and 1596.

Gray *et al.* say the first of these findings suggests "the mechanisms driving AMO variability have operated in a similar fashion for (at least) the previous 500 years," and "trace-gas forcing has yet to significantly affect the low-frequency component of THC [thermohaline circulation] variability." Their work also suggests trace-gas forcing has yet to significantly affect the near-surface air temperature of the Northern Hemisphere, and the identification of the start of a new warming phase in the mid-1990s suggests the supposedly record temperatures of the past decade or so may have been driven more by natural AMO variability than increasing greenhouse gas concentrations.

The most intense warm phase of the AMO record of Gray *et al.* occurred near the end of the time frame associated with evidence of what could be called the "Little" Medieval Warm Period, when global air temperature may have been significantly warmer than it has been at any subsequent time, clearly evident in Gray *et al.*'s reconstruction of North Atlantic SST anomalies. Thus the evidence continues to mount for the existence of a warm period in the general vicinity of the 1500s, when the air's CO₂ content was much less than it is today.

von Storch *et al.* (2004) used a coupled atmosphere-ocean model simulation of the climate of the past millennium as a surrogate climate to test the skill of the empirical reconstruction methods used by Mann *et al.* (1998, 1999) in deriving their thousand-year "hockey stick" temperature history of the Northern Hemisphere. They generated several pseudo-proxy temperature records by sampling a subset of the model's simulated grid-box temperatures representative of the spatial distribution of the real-world proxy temperature records used by Mann *et al.* They degraded these pseudo-proxy records with statistical noise, regressed the results against the measured temperatures of the historical record, and used the relationships thus derived to construct a record they could compare against their original model-derived surrogate temperature history.

The six scientists discovered the centennial variability of Northern Hemisphere temperature was underestimated by the regression-based methods they applied, suggesting past variations in real-world temperature "may have been at least a factor of two larger than indicated by empirical reconstructions."

The consequences of this result are readily evident in the reduced degree of Little Ice Age cooling and Medieval warming that resulted from the techniques employed by Mann *et al.*

In an accompanying commentary on von Storch *et al.*'s paper, Osborn and Briffa (2004) state, "if the true natural variability of [Northern Hemisphere] temperature is indeed greater than is currently accepted, the extent to which recent warming can be viewed as 'unusual' would need to be reassessed." The need for this reassessment is also suggested by what von Storch *et al.* refer to as "empirical methods that explicitly aim to preserve low-frequency variability (Esper *et al.*, 2002)," which show much more extreme Medieval warming and Little Ice Age cooling than do the reconstructions of Mann *et al.*

These observations indicate the temperature record of Esper *et al.* is likely to be much more representative of reality than is the IPCC-endorsed record of Mann *et al.* The lion's share of the warming experienced since the end of the Little Ice Age occurred well before mankind's CO₂ emissions significantly perturbed the atmosphere, suggesting most of the post-Little Ice Age warming was due to something other than rising atmospheric CO₂ concentrations. That further suggests the lesser warming of the latter part of the twentieth century also may have been due to something else.

Cook *et al.* (2004) reviewed the work of Esper *et al.* (2002) and conducted further analyses of the data the latter team of scientists had employed in its reconstruction effort. Cook *et al.* determined the "strongly expressed multi-centennial variability [of the Esper *et al.* reconstruction] is highly robust over the AD 1200–1950 interval, with strongly expressed periods of 'Little Ice Age' cooling indicated prior to AD 1900," and "persistently above-average temperatures in the AD 960–1050 interval also suggest the large-scale occurrence of a 'Medieval Warm Period' in the Northern Hemisphere extra-tropics."

Cook *et al.* draw this conclusion despite what they describe as strong criticism personally communicated to them by R.S. Bradley of the Mann *et al.* group of researchers. The existence of a global Medieval Warm Period is hotly debated and critical to the climate change debate, because if Earth was as warm as it is today a thousand or more years ago, when the air's CO₂ concentration was more than 100 ppm less than it is today, there is no compelling reason to believe atmospheric CO₂ concentrations had anything to do with the global warming of the past

century.

Moberg *et al.* (2005) presented a new temperature history of the Northern Hemisphere spanning the past two millennia, produced from two sources of paleoclimatic data: tree rings, which capture very high frequency climate information, and lake and ocean sediments, which "provide climate information at multi-centennial timescales that may not be captured by tree-ring data."

The new temperature history clearly revealed the existence of one full cycle of the roughly 1500-year climatic oscillation that reverberates throughout the Holocene and across prior glacial and interglacial periods alike (Oppo *et al.*, 1998; Raymo *et al.*, 1998; McManus *et al.*, 1999). Moberg *et al.* noted, for example, "high temperatures—similar to those observed in the twentieth century before 1990—occurred around AD 1000 to 1100, and minimum temperatures that are about 0.7°C below the average of 1961–90 occurred around AD 1600," whereas the twentieth century has seen a return to a new period of relative warmth.

Moberg *et al.* say the low-frequency variability missing from the temperature reconstructions of Mann *et al.* originates from a set of 11 non-tree-ring proxy climate records that cover most of the past two millennia, nine of which already had been calibrated to local/regional temperatures by their developers. Moberg *et al.* say simple averages of temperature proxy series, such as the ones they used, "can yield adequate estimates of Northern Hemisphere century-scale mean-temperature anomalies," citing the work of von Storch *et al.* (2004). When simple averaging is all that is done, as is evident in Moberg *et al.*'s graphical results, the Medieval Warm Period is observed to peak just prior to AD 900 and is strongly expressed between about AD 600 to 1100, very possibly the most correct temperature reconstruction of all (see Figure 4.2.3.1).

Figure 4.2.3.1 shows the final twentieth century temperature of the record developed by Moberg *et al.* is cooler than the temperatures of the entire 500-year time span of the MWP. It is only when the directly measured instrumental temperatures of the latter part of the twentieth century are added to the new temperature history that the Swedish and Russian scientists observe a recent ("post-1990") modern warming that "appears to be unprecedented" over the prior two millennia. Note they say the warming *appears* to be unprecedented, for one cannot make a definitive comparative judgment on the matter when the two types of data involved are significantly

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different from each other. One cannot compare real apples with reconstructed oranges, especially when the apples may have been contaminated by a factor (the growing urban heat island and land-use change effects) that likely had little or no influence on the oranges.

McIntyre and McKittrick (2005) also analyzed the procedures used by Mann *et al.* (1998) to develop their hockey stick temperature reconstruction. In an analysis of an unusual data transformation employed by Mann *et al.*, which strongly affects the resulting principal components (PCs) of their tree-ring-based temperature reconstructions, the two researchers discovered the unusual method nearly always produced a hockey stick-shaped first principal component (PC1) when tested on persistent red noise. “In effect,” they write, “the Mann *et al.* (1998) data transformation results in the PC algorithm mining the data for hockey stick patterns.”

The researchers also demonstrate the data

transformation used by Mann *et al.* “effectively selects only one species (bristlecone pine) into the critical North American PC1, making it implausible to describe it as the ‘dominant pattern of variance.’” The selected tree-ring records were ones that had been developed and analyzed by Graybill and Idso (1993), who suggested they were particularly good candidates for exhibiting CO₂-induced increases in growth as opposed to temperature-induced increases in growth, as assumed by Mann *et al.* Graybill and Idso describe in detail how they investigated “the possibility that changes in climate during the past century might be responsible for the unusual increases in ring width growth” that were exhibited by the trees, “considering temperature, precipitation and computed drought values,” and it is their stated conclusion—clearly available for Mann *et al.* to read before using their data—that “it is notable that trends of the magnitude observed in 20th century ring width growth are conspicuously lacking in all of the time

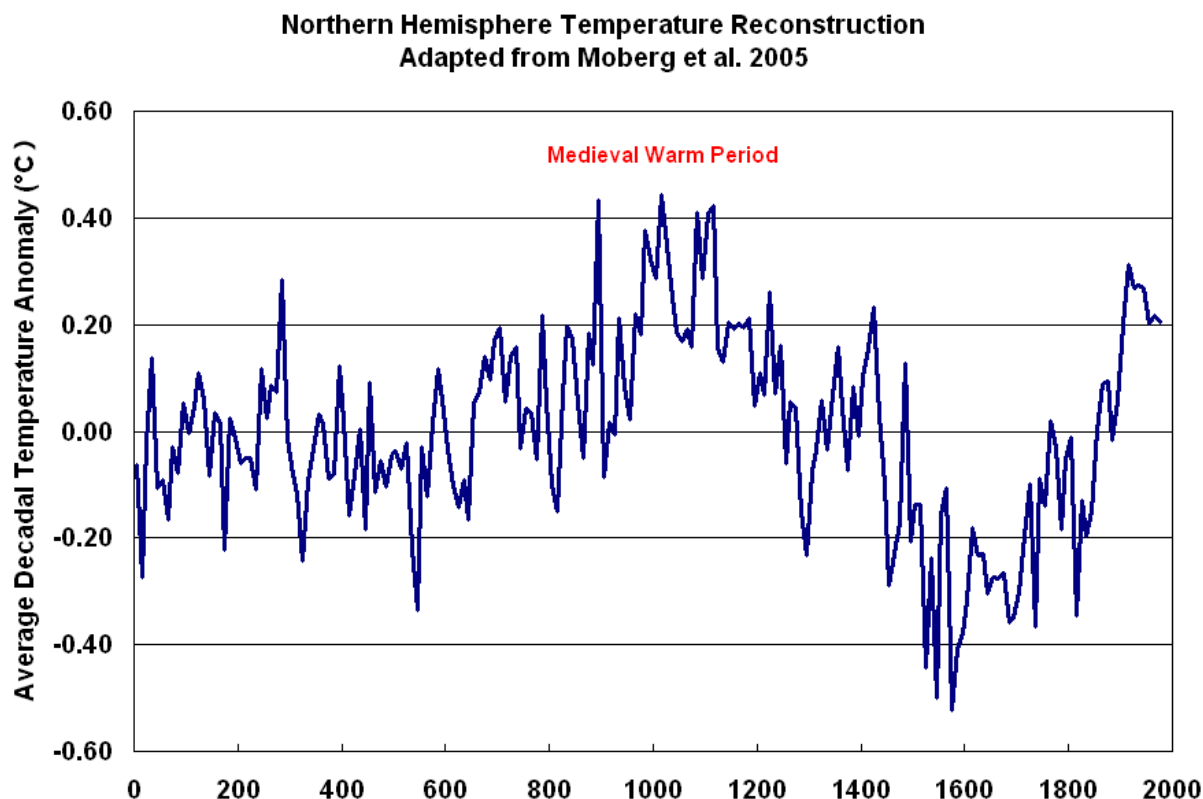


Figure 4.2.3.1. Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data covering the past 2,000 years. Adapted from Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* 433: 613–617.

series of instrumented climatic variables that might reasonably be considered growth-forcing in nature.” These facts are particularly “disquieting,” as McIntyre and McKittrick put it, “given that the NOAMER PC1 has been reported to be essential to the shape of the Mann *et al.* (1998) Northern Hemisphere temperature reconstruction.”

McIntyre and McKittrick also show the Mann *et al.* (1998) benchmarks for significance of their Reduction of Error statistic were “substantially understated,” and using a range of cross-validation statistics, they show Mann *et al.*’s reconstruction “lacks statistical significance.”

Esper *et al.* (2005) selected four representations of Earth’s surface air temperature history over the past thousand years (Jones *et al.*, 1998; Mann *et al.*, 1999; Briffa, 2000; Esper *et al.*, 2002) for inclusion in an analysis designed to reveal the significance of problems associated with some of those histories. They note “these records were developed using tree ring data alone or using multi-proxy data, and are reported to represent different regions (e.g. Northern Hemisphere (NH) extra-tropics, or full NH),” thereby highlighting two of several factors (different types of data, different areas of applicability) that lead to different results. The four researchers also investigated methodological differences, including “using scaling or regression, the calibration time period, and smoothing data before calibration.” They also point out different histories sometimes represent different seasons of the year; they either include or exclude sea surface temperatures; the available data are “more uncertain back in time”; and the record “becomes biased towards Europe, North America, and areas in Asia” moving back in time.

Reporting on the results of their analyses of the effects of scaling and regression approaches applied in the recent scientific literature to proxy-based temperature records, Esper *et al.* (2005) state, “these various approaches alone can result in differences in the reconstructed temperature amplitude [“measured from the coldest to warmest decades”] of about 0.5°C.” This difference, they write, is “equivalent to the mean annual temperature change for the Northern Hemisphere reported in the last IPCC report for the 1000–1998 period.” In addition, they point out “consideration of temporally changing spatial coverage and uncertainty in both the instrumental and proxy data, as expressed by confidence limits accompanying such records, would further increase the range of amplitude estimates over the past millennium.”

Esper *et al.* also note, “when linear regression is used for calibration, the variance of a proxy record remains below that of the target data, leaving the visual impression that the recent dynamics are substantially larger than the historic ones when splicing such records together,” which is precisely the impression conveyed when the modern instrumental record is attached to the end of calibrated proxy data, as in the hockey stick temperature record of Mann *et al.* (1999).

Asami *et al.* (2005) derived a monthly resolved 213-year (1787–2000) time series of carbon and oxygen isotope variations measured in a 273-cm-long coral core retrieved from a *Porites labata* colony located on the northwestern coast of Guam, where it had been exposed to open sea surface conditions over the entire period of its development. “On the basis of the Guam $\delta^{18}\text{O}$ coral record,” according to the six scientists, “the early 19th century (1801–1820) was the coolest in the past 210 years, which is consistent with SST reconstructions 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 the early nineteenth century on, “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.

The existence of the Little Ice Age, missing from the Mann *et al.* (1998, 1999) reconstruction, is clearly manifest at the beginning of the Guam coral record and at about the same time in the New Caledonia coral record. The Guam coral record also depicts essentially continuous warming from about 1815, just as the Esper *et al.* record does, whereas the Mann *et al.* record does not depict warming until after 1910, about a century later. A 0.75°C rise in temperature from the start of the warming until the end of the twentieth century is not at all unusual, since it begins at one of the coldest points of the coldest multi-century period (the Little Ice Age) of the entire Holocene, the current interglacial.

The extreme cold of the early 1800s and the warming that followed it were not caused by changes in the air’s CO₂ concentration. Instead, a reversal of the forces that produced the cold in the first place (Asami *et al.* mention a decrease in solar irradiance and large volcanic eruptions) likely led to the subsequent warming. This represents the entirely natural recovery of Earth from the global chill of one

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of the coldest portions of the coldest multi-century period of the past 10,000 years.

D'Arrigo *et al.* (2006) note the Northern Hemispheric temperature reconstruction of Mann *et al.* (1999) “demonstrates minimal temperature amplitude (e.g., during the ‘Medieval Warm Period’ and ‘Little Ice Age’) while others (Briffa, 2000; Esper *et al.*, 2002; Cook *et al.*, 2004; Moberg *et al.*, 2005) exhibit more pronounced variability.” To determine the reasons for this discrepancy, they assembled mostly tree-ring width (but some density) data from living and subfossil wood of coniferous tree species found at 66 high-elevation and latitudinal treeline North American and Eurasian sites, analyzing these data via both standard (STD) and regional curve standardization (RCS) detrending techniques. STD (used by Mann *et al.*) does not accurately capture the low-frequency variability required to compare the temperatures of periods separated in time by many hundreds of years or more. In addition, D'Arrigo *et al.* report, “the North American data are much improved with new or extended millennial-length records and updates of most of the data sets until at least the late 1990s.” Also, they did not use the long bristlecone pine datasets from Colorado and California that Mann *et al.* employed, “as many appear to portray a mixed precipitation and temperature signal (in addition to a purported CO₂ fertilization effect),” and they did not use the Mackenzie Mountains, Boreal, Upperwright, and Gotland datasets utilized by Esper *et al.* (2002) because they “(1) did not demonstrate a significant temperature signal on the local to regional scale, (2) displayed significant correlations with precipitation, or (3) were located at lower latitudes than those compiled for the present analysis.”

D'Arrigo *et al.*'s STD and RCS Northern Hemisphere temperature reconstructions spanned the period AD 713–1995. They found “the long-term trends of the STD reconstruction most closely match the Mann *et al.* (1999) and Jones *et al.* (1998) series, whereas the RCS reconstruction compares best with the Esper *et al.* (2002) and Cook *et al.* (2004) series.” This observation, they write, “validates the hypothesis (Esper *et al.*, 2004) that one reason for the relative lack of long-term variability in the work of Mann *et al.* (1999) was their use of standard detrending procedures that removed low-frequency variation.” They conclude “the RCS reconstruction is superior to the more traditional STD method with regards to the ability to retain low-frequency (centennial to multi-centennial) trends.”

In comparing the temperatures of the Medieval Warm Period with those of the Current Warm Period, based on the six longest (>1000 years) chronologies they analyzed, D'Arrigo *et al.* conclude “the recent period does not look particularly warmer compared to the MWP.” They note the mean of the six series does depict a warmer CWP, but they describe this apparent relationship as “a bias/artifact in the full RCS reconstruction (and likely in many of the other reconstructions) where the MWP, because it is expressed at different times in the six long records, is ‘averaged out’ (i.e., flattened) compared to the recent period which shows a much more globally consistent signal.”

D'Arrigo *et al.* conclude “not enough proxy records yet exist for this time,” meaning the MWP. Working with the records they had, they found “late twentieth century warming exceeds peak MWP conditions by 0.67°C when comparing decadal averages (960–969 (reconstruction) = -0.12°C versus 1991–2000 (instrumental) = 0.55°C).” This conclusion, of course, is based on an “apples and oranges” comparison, and the three researchers report, “peak twentieth century warmth for the period covered only by the proxy data (1937–1946, 0.17°C) exceeds peak MWP conditions by 0.29°C,” a significantly smaller number than that obtained by comparing the reconstructed and instrumental results.

A further confounding fact, according to D'Arrigo *et al.*, is the “apparent decrease in recent temperature sensitivity for many northern sites ... with divergence from instrumental temperatures after ~1986.” So great has this divergence been that the late 1990s instrumental temperatures are essentially a full degree Centigrade higher than those of the proxy reconstructions. The three researchers conclude, “until valid reasons for this phenomenon have been found, [we] can only question the ability of tree-ring data to robustly model earlier periods that could have been similarly warm (or warmer) than the present.” To resolve the issue of the relative warmth of the CWP compared to that of the MWP, they suggest “many long records from new NH locations and updating of existing records to the present are required.”

D'Arrigo *et al.* (2008) tackled the divergence problem, which they describe as “an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings.” This problem was “detected in tree-ring width and density records from many circumpolar northern latitude sites since around the middle 20th

century.” They “review[ed] the current literature published on the divergence problem to date, and assess[ed] its possible causes and implications.”

The four researchers identified several possible causes for the divergence: moisture stress, nonlinear or threshold responses to warming, local pollution, delayed snowmelt, changes in seasonality, differential responses to maximum and minimum temperatures, global dimming, methodological issues related to “end effects,” biases in instrumental target data, the modeling of such data, declining stratospheric ozone concentrations, increased UV-B radiation at ground level, and “an upward bias in surface thermometer temperature measurements in recent years related to heat island effects.”

D’Arrigo *et al.* report their review “did not yield any consistent pattern that could shed light on whether one possible cause of divergence might be more likely than others,” leading them to conclude “a combination of reasons may be involved that vary with location, species or other factors, and clear identification of a sole cause for the divergence is probably unlikely.”

Ljungqvist (2010) developed a 2,000-year

temperature history of the extra-tropical portion of the Northern Hemisphere (i.e., that part covering the latitudinal range 30–90°N) based on 30 temperature-sensitive proxy records with annual to multi-decadal resolution: two historical documentary records, three marine sediment records, five lake sediment records, three speleothem $\delta^{18}\text{O}$ records, two ice-core $\delta^{18}\text{O}$ records, four varved thickness sediment records, five tree-ring width records, five tree-ring maximum latewood density records, and one $\delta^{13}\text{C}$ tree-ring record. Ljungqvist did not employ tree-ring width records from arid and semi-arid regions, because they may have been affected by drought stress and thus may not have shown a linear response to warming if higher summer temperatures also reduced the availability of water, as suggested by the work of D’Arrigo *et al.* (2006) and Loehle (2009).

The results of the Swedish scientist’s efforts are depicted in Figure 4.2.3.2. Ljungqvist states this temperature history depicts “a Roman Warm Period c. AD 1–300, a Dark Age Cold Period c. AD 300–800, a Medieval Warm Period c. AD 800–1300 and a Little Ice Age c. AD 1300–1900, followed by the twentieth-century warming.” These alternating

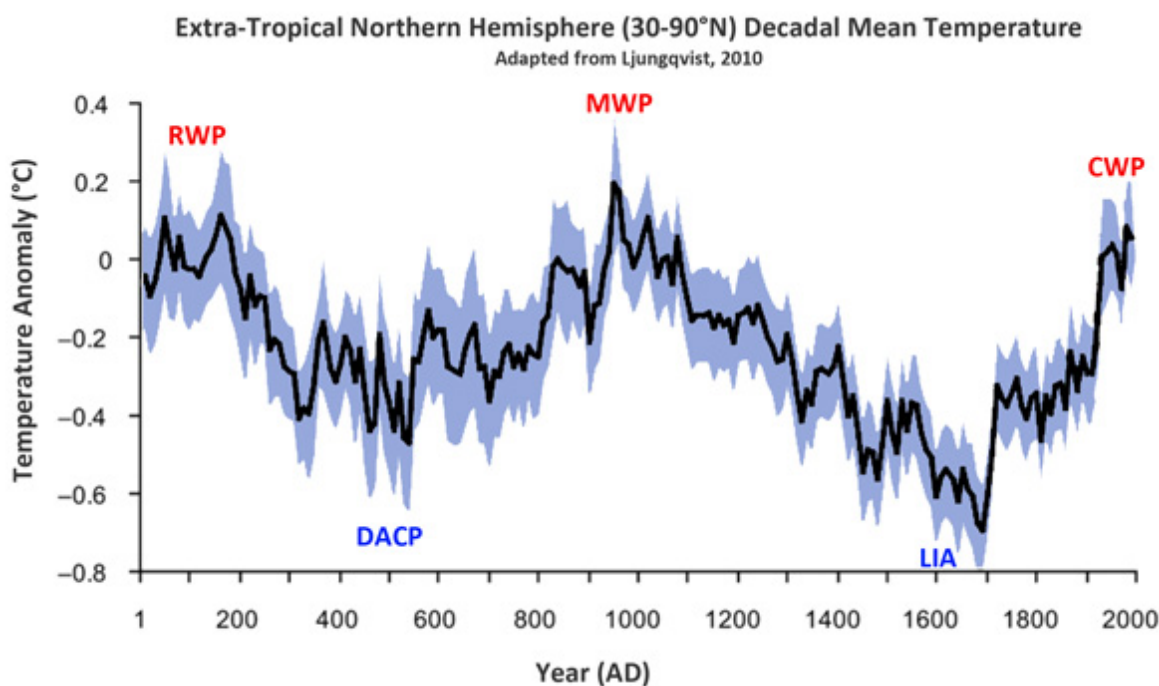


Figure 4.2.3.2. Reconstructed extra-tropical (30-90°N) mean decadal temperature variations relative to the 1961-1990 mean of the variance-adjusted 30-90°N CRUTEM3+HadSST2 instrumental temperature data of Brohan *et al.* (2006) and Rayner *et al.* (2006). Adapted from Ljungqvist, F.C. 2010. A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler* 92A: 339–351.

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warm/cold periods, he writes, “probably represent the much discussed quasi-cyclical *c.* 1470 $\pm$ 500-year Bond Cycles (Bond and Lotti, 1995; O’Brien *et al.*, 1995; Bond *et al.*, 1997, 2001; Oppo, 1997),” which “affected both Scandinavia and northwest North America synchronically (Denton and Karlen, 1973)” and have “subsequently also been observed in China (Hong *et al.*, 2009a,b), the mid-latitude North Pacific (Isono *et al.*, 2009) and in North America (Viau *et al.*, 2006), and have been shown to very likely have affected the whole Northern Hemisphere during the Holocene (Butikofer, 2007; Wanner *et al.*, 2008; Wanner and Butikofer, 2008), or even been global (Mayewski *et al.*, 2004).”

Ljungqvist also notes “decadal mean temperatures in the extra-tropical Northern Hemisphere seem to have equaled or exceeded the AD 1961–1990 mean temperature level during much of the Roman Warm Period and the Medieval Warm Period,” and “the second century, during the Roman Warm Period, is the warmest century during the last two millennia.” In addition, “the highest average temperatures in the reconstruction are encountered in the mid to late tenth century,” during the Medieval Warm Period. He warns the temperature of the last two decades “is possibly higher than during any previous time in the past two millennia,” but adds, “this is only seen in the instrumental temperature data and not in the multi-proxy reconstruction itself.”

Ljungqvist’s study is especially important because it utilizes “a larger number of proxy records than most previous reconstructions” and “substantiates an already established history of long-term temperature variability.”

Syun-Ichi Akasofu (2010), founding director of the International Arctic Research Center of the University of Alaska-Fairbanks (USA), employed “openly available data on sea level changes, glacier retreat, freezing/break-up dates of rivers, sea ice retreat, tree-ring observations, ice cores and changes of the cosmic-ray intensity, from the year 1000 to the present” to show Earth’s recovery from the Little Ice Age “has proceeded continuously, roughly in a linear manner, from 1800–1850 to the present,” with the rate of recovery being about 0.5°C/century. He suggests Earth is “still in the process of recovery from the LIA,” being brought about by whatever was responsible for the mean linear warming of the twentieth century as modulated by a “multi-decadal oscillation of a period of 50 to 60 years” that is superimposed upon it and “peaked in 1940 and 2000, causing the halting of warming temporarily after

2000.” Extending these two phenomena into the future, Akasofu predicts the non-CO₂-induced temperature increase over the twenty-first century will be 0.5°C $\pm$ 0.2°C, rather than the much greater 4°C $\pm$ 2°C predicted by the IPCC.

Ljungqvist *et al.* (2012) write, “a number of Northern Hemispheric (NH) temperature reconstructions covering the last 1–2 millennia, using temperature-sensitive proxy data, have been made to place the observed 20th century warming into a long-term perspective.” They state, “these studies generally agree on the occurrence of warmer conditions ca. 800–1300 AD and colder conditions ca. 1300–1900 AD, followed by a strong warming trend in the 20th century,” noting “the earlier warm period is usually referred to as the Medieval Warm Period ... whereas the later colder period is usually referred to as the Little Ice Age.” “Related to this issue,” they continue, “is the question of whether or not the current warmth has exceeded the level and geographic extent of the warmth in the last millennium.”

Ljungqvist *et al.* developed “a new reconstruction of the spatio-temporal patterns of centennial temperature variability over the NH land areas for the last twelve centuries based on 120 proxy records,” which were “retrieved from a wide range of archives including, but not limited to, ice-cores, pollen, marine sediments, lake sediments, tree-rings, speleothems and historical documentary data.” With respect to how big an improvement their database is over those used in prior studies of this type in terms of the amount and distribution of data employed, they present a list of antecedent analyses where the number of proxy records used ranged from only three to 46 (compared to their 120), and where the number of records with annual resolution ranged from only three to 30, whereas their study included 49 such annual-resolution records.

The result of Ljungqvist *et al.*’s work is depicted in Figure 4.2.3.3. The four Swedish scientists report, “during the 9th to 11th centuries there was widespread NH warmth comparable in both geographic extent and level to that of the 20th century.” They also note their results indicate “the rate of warming from the 19th to the 20th century is clearly the largest between any two consecutive centuries in the past 1200 years,” but this is not surprising, given that the Little Ice Age is universally recognized as having been the coldest multi-century period of the current interglacial (Barclay *et al.*, 2009; Briner *et al.*, 2009; Menounos *et al.*, 2009) and its most extensively glaciated period (Calkin *et al.*, 2001;

Clague *et al.*, 2004; Joerin *et al.*, 2006). Recovery from such an extremely cold condition would be expected to be quite dramatic.

In light of the results depicted in Figure 4.2.3.3, it should be clear there is nothing unusual, unnatural, or unprecedented about Earth's current level of warmth when compared to that of the Medieval Warm Period, when there was significantly less CO₂ in the air than

report “the level of warmth during the peak of the MWP in the second half of the 10th century, equal[s] or slightly exceed[s] the mid-20th century warming.” This result, they say, is “in agreement with the results from other more recent large-scale multi-proxy temperature reconstructions,” citing among others the studies of Moberg *et al.* (2005), Ljungqvist (2010), and Ljungqvist *et al.* (2012).

As for the timing of the MWP in different parts of the extra-tropical Northern Hemisphere, they report Ljungqvist *et al.* (2012) showed, “on centennial time-scales, the MWP is no less homogeneous than the Little Ice Age if all available proxy evidence, including low-resolution records are taken into consideration in order to give a better spatial data coverage.”

This research adds to the growing body of real-world evidence demonstrating the global nature and temporal consistency of the MWP. It also confirms the MWP's peak temperatures throughout the extratropical Northern Hemisphere strongly rivaled or exceeded those of the Current Warm Period, even though the

atmospheric CO₂ concentrations of today are 40 percent greater than they were during the MWP. Taken together, these observations strongly suggest the warmth of the Current Warm Period is due to something other than the current high atmospheric CO₂ concentration.

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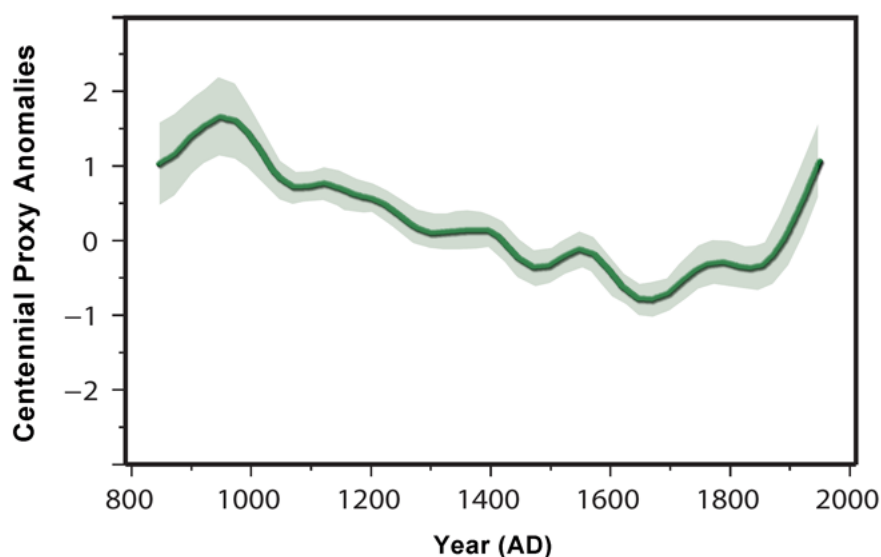


Figure 4.2.3.3. Mean whole-year centennial temperature proxy anomalies (standard deviations from the AD 1000-1899 mean) vs. year AD, where the shaded area represents ± 2 standard errors. Adapted from Ljungqvist, F.C., Krusic, P.J., Brattstrom, G., and Sundqvist, H.S. 2012. Northern Hemisphere temperature patterns in the last 12 centuries. *Climate of the Past* **8**: 227–249.

there is currently (~280 ppm then vs. ~400 ppm now). There is no compelling reason to attribute the post-Little Ice Age warming to changes in the concentration of this trace gas of the atmosphere.

Christiansen and Ljungqvist (2012) used a variety of temperature proxies “shown to relate to local or regional temperature,” together with a reconstruction method shown to “confidently reproduce low-frequency variability,” to develop a new multi-proxy reconstruction of the mean temperature of the extratropical Northern Hemisphere (30–90°N) stretching back to the BC/AD transition. This two-millennia-long temperature history shows a well-defined Medieval Warm Period with “a well-defined peak in the period 950–1050 AD with a maximum temperature anomaly of 0.6°C” relative to the reference period of 1880–1960, the timing of which they say “is in agreement with the reconstructions of Esper *et al.* (2002) and Ljungqvist (2010).” They

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4.2.4 Regional Manifestations of the Non-Uniqueness of Current Temperatures

Sections 4.2.1 through 4.2.3 present evidence temperatures of the past several decades are not unusual, unnatural, or unprecedented on a hemispheric or global scale, contrary to the conclusions of the IPCC. The Roman and Medieval Warm Periods were likely as warm as or warmer than the Current Warm Period. And since temperatures were as warm when atmospheric CO₂ concentrations were much lower than they are now, there are valid empirical reasons to conclude the temperature increase of the past century has occurred independently of the concomitant 40 percent increase in atmospheric CO₂. Real-world observations reveal the Current Warm Period is simply a manifestation of the natural progression of a persistent millennial-scale climate oscillation that regularly brings Earth several-hundred-year periods of modestly higher and lower temperatures independent of variations in atmospheric CO₂ concentration.

In this section, additional evidence is presented by region that there is nothing unusual, unnatural, or unprecedented about current temperatures. Although much of the material focuses on the reality and temperatures of the Roman and Medieval Warm Periods, some discussion is included on temperatures both before and after these important climate epochs.

4.2.4.1 Africa

Based on the temperature and water needs of the crops cultivated by the first agropastoralists of southern Africa, Huffman (1996) constructed a climate history of the region using archaeological evidence acquired from various Iron Age settlements. Dated relic evidence of the presence of cultivated sorghum and millets was considered by Huffman to be so strong as to prove the climate of the subcontinent-wide region must have been warmer and wetter than it is today from approximately AD 900–1300, for these crops cannot be grown in this part of southern Africa under current climatic conditions, which are much too cool and dry.

Other evidence for this conclusion comes from Tyson *et al.* (2000), who obtained a quasi-decadal record of oxygen and carbon-stable isotope data from a well-dated stalagmite of Cold Air Cave in the Makapansgat Valley (30 km southwest of Pietersburg, South Africa). They augmented those data with five-year-resolution temperature data reconstructed from color variations in banded growth-layer laminations of the stalagmite derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981–1995, which had a correlation of +0.78 that was significant at the 99% confidence level. This record revealed a significantly warmer-than-present period that began prior to AD 1000 and lasted to about AD 1300 (see Figure 4.2.4.1.1). Tyson *et al.* report the “maximum warming at Makapansgat at around 1250 produced conditions up to 3–4°C hotter than those of the present.”

Holmgren *et al.* (2001) used Cold Air Cave records to derive a 3,000-year temperature record for South Africa that revealed several multi-century warm and cold periods. They found a dramatic warming at approximately AD 900, when temperatures reached a level 2.5°C higher than that prevailing at the time of their analysis of the data (see Figure 4.2.4.1.2).

Holmgren *et al.* (2003) developed a 25,000-year temperature history from a stalagmite retrieved from Cold Air Cave based on $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ measurements dated by ^{14}C and high-precision thermal ionization mass spectrometry using the $^{230}\text{Th}/^{234}\text{U}$ method. The nine researchers found “cooling is evident from ~6 to 2.5ka [thousand years before present, during the long interval of coolness that preceded the Roman Warm Period], followed by warming between 1.5 and 2.5 ka [the Roman Warm Period] and briefly at ~AD 1200 [the Medieval Warm Period, which followed the Dark

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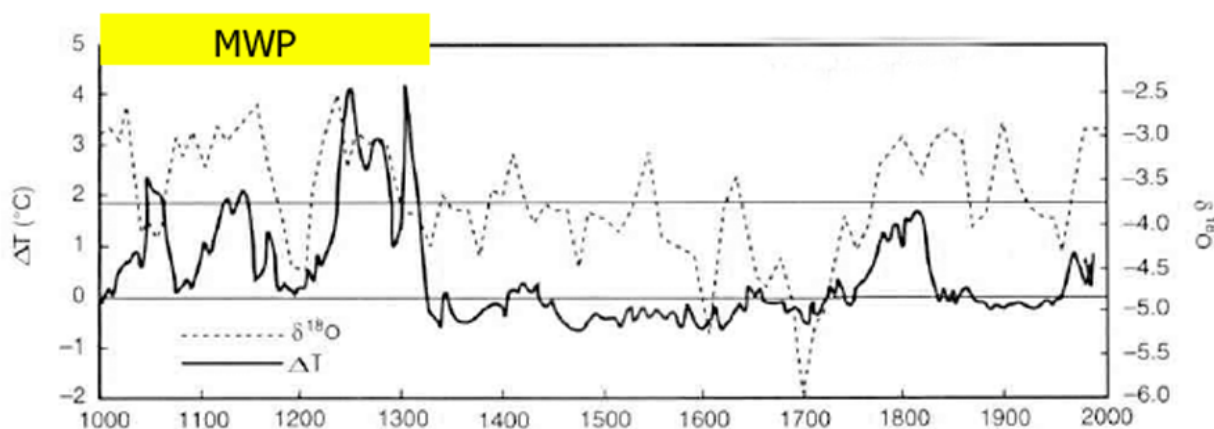


Figure 4.2.4.1.1. Temperature reconstruction from Cold Air Cave in the Makapansgat Valley, South Africa. Adapted from Tyson, P.D., Karlén, W., Holmgren, K., and Heiss, G.A. 2000. The Little Ice Age and medieval warming in South Africa. *South African Journal of Science* **96**: 121–126.

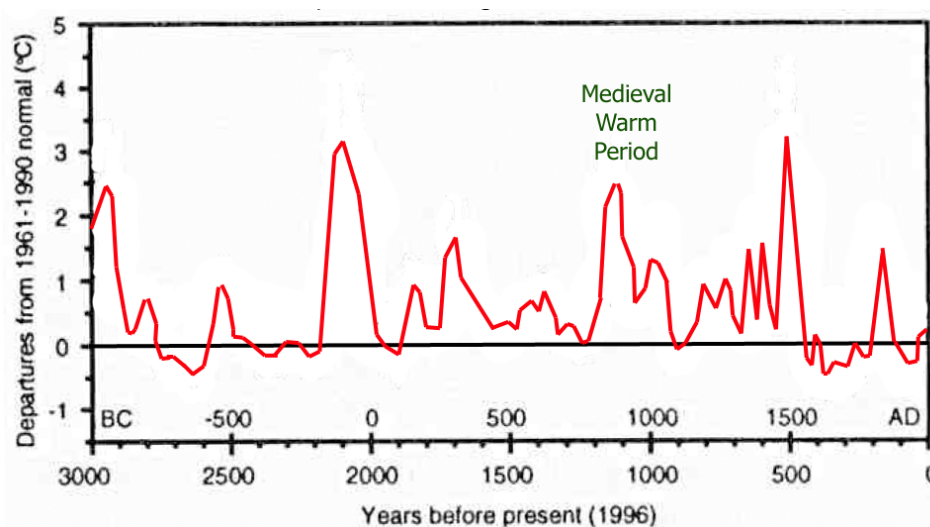


Figure 4.2.4.1.2. Temperature reconstruction from Cold Air Cave in the Makapansgat Valley, South Africa. Adapted from Holmgren, K., Tyson, P.D., Moberg, A., and Svanered, O. 2001. A preliminary 3000-year regional temperature reconstruction for South Africa. *South African Journal of Science* **97**: 49–51.

Ages Cold Period],” after which “maximum Holocene cooling occurred at AD 1700 [the depth of the Little Ice Age].” They also note “the Little Ice Age covered the four centuries between AD 1500 and 1800 and at its maximum at AD 1700 represents the most pronounced negative $\delta^{18}\text{O}$ deviation in the entire record.” This temperature record reveals the existence of all of the major millennial-scale oscillations of climate that are evident in data collected from regions surrounding the North Atlantic Ocean.

Working with the vertical sediment profile of

Ocean Drilling Program Hole 658C, which was cored off Cap Blanc, Mauritania (20°45'N, 18°35'W) at a water depth of 2,263 meters, DeMenocal *et al.* (2000) analyzed various parameters, including planktonic foraminiferal assemblage census counts, from which they calculated warm- and cold-season sea surface temperatures based on transfer functions derived from faunal analyses of 191 other Atlantic core tops. The authors report finding a series of abrupt millennial-scale cooling events followed by compensatory warming events that “appear to have involved the

entire North Atlantic basin (O'Brien *et al.*, 1995; Keigwin, 1996; Bond *et al.*, 1997; Bianchi and McCave, 1999; Bond *et al.*, 1999), recurred with a $\sim 1,500 \pm 500$ year period throughout glacial and interglacial intervals (O'Brien *et al.*, 1995; Bond *et al.*, 1997; Bianchi and McCave, 1999; Bond *et al.*, 1999), were accompanied by terrestrial climate changes (COHMAP Members, 1988; Gasse and Van Campo, 1999), and involved large-scale ocean and atmosphere reorganizations that were completed within decades or centuries (Alley *et al.*, 1993).” The four researchers go on to state, “these climate perturbations continue to persist during ‘our time,’” noting “the most recent of these, the Little Ice Age, ended in the late 19th century” and “some of the warming since that time may be related to the present warming phase of this millennial-scale oscillation.” They add, “the warming in recent decades is unprecedented relative to the past millennium.”

This work further revealed that between about AD 800 and 1050 the “Medieval Warm Period,” as they describe it, “was only marginally warmer than present.” The graphical presentation of their results (see Figure 4.2.4.1.3) depicts between 0.6 and 1.2°C for the cold and warm season SST estimates, respectively.

Figure 4.2.4.1.3 shows the peak warmth of the Medieval Warm Period, which occurred roughly one thousand years ago, was approximately 1.2°C higher than what their data show for the end of the twentieth century. There is some uncertainty, however, with respect to what year corresponds with the authors’ definition of the present. The SST graphic reproduced from their paper indicates the “present” corresponds to around the year 1900, whereas the text of their paper indicates the first data point represents conditions from between a sediment depth of 0 and 2 cm and the core “was continuously subsampled at 2-cm intervals, which is equivalent to between 50 and 100 years temporal resolution.” Because of this ambiguity and erring on the side of caution, it can be concluded the MWP warmth was about the same as the warmth of the past two to three decades. This assessment is arrived at by noting the surface air temperature of the globe has warmed by about 0.7 °C over the past 100 years, which falls between the 0.6 and 1.2°C sea surface temperature differential between the peak warmth of the MWP and that of deMenocal *et al.*’s “present.”

Lamb *et al.* (2003) provide strong evidence for a hydrologic fingerprint of the Medieval Warm Period in Central Kenya in a study of pollen data obtained

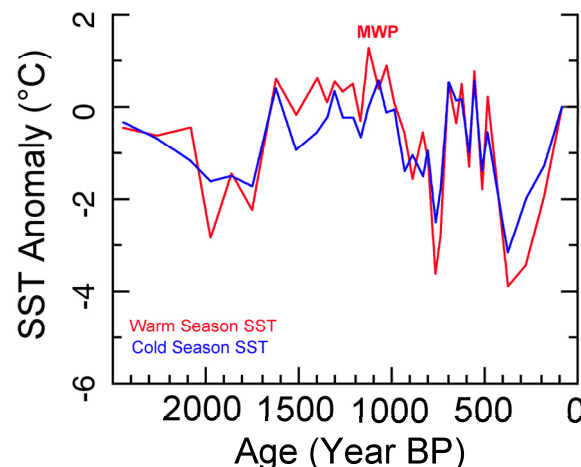


Figure 4.2.4.1.3. West African sea surface temperature vs. time. Adapted from deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M. 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* **288**: 2198–2202.

from a sediment core taken from Crescent Island Crater, a sub-basin of Lake Naivasha. Of particular interest is the strong similarity between their results and those of Verschuren *et al.* (2000). The most striking of these correspondences occurred over the period AD 980 to 1200, when lake level was at a 1,100-year low and woody taxa were significantly underrepresented in the pollen assemblage.

Stager *et al.* (2003) analyzed diatom types and abundances found in a sediment core retrieved from Pilkington Bay, Lake Victoria, East Africa (0°18'N, 33°20'E), relating them to the ratio of precipitation to evaporation (P/E) and/or lake depth. This revealed, they write, “major droughts occurred ca. 1200–600 yr B.P. during Europe’s Medieval Warm Period.”

Fraedrich *et al.* (1997) examined records of historical maximum and minimum flood-level time series of the River Nile (AD 622–1470) “to identify abrupt climate changes by applying global and local analysis techniques: the Mann-Kendall test and a non-hierarchical cluster analysis method to improve the Mann-Kendall test; a multi-scale moving *t*-test with correction to the degree of freedom and an anti-symmetric wavelet transform.” They noted the River Nile and its source regions, with their “links to other climatic zones of the world, may represent a key region to demonstrate the possible global nature of climate variability.” The four researchers report “three climate epochs of longer time-scales, AD 622–1078, 1079–1325 and 1326–1470, coinciding with

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larger-scale climate changes reported in Europe: a relatively cool age, the Little Climatic Optimum of the Middle Ages, and an interim period before the Little Ice Age.”

Kondrashov *et al.* (2005) applied advanced spectral methods to fill data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels on the Nile River over the 1,300-year period AD 622–1922. Several statistically significant periodicities were noted, including cycles at 256, 64, 19, 12, 7, 4.2, and 2.2 years. With respect to the causes of these cycles, the three researchers state the 4.2- and 2.2-year oscillations are likely due to El Niño-Southern Oscillation variations, the 7-year cycle may be related to North Atlantic influences, and the longer-period oscillations could be due to astronomical forcings. They also note the annual-scale resolution of their results provides a “sharper and more reliable determination of climatic-regime transitions” in tropical east Africa, including the documentation of fairly abrupt shifts in river flow at the beginning and end of the Medieval Warm Period.

Lamb *et al.* (2007) developed a 2,000-year history of effective precipitation based upon oxygen and carbon isotope and pollen stratigraphy data derived from a sediment core taken from Lake Hayq (11°21'N, 39°43'E) on the eastern margin of the north-central highlands in South Wollo, Ethiopia. This record revealed, they write, a “similar, but slightly moister climate than today, with high interdecadal variability, prevailed from AD 800 to AD 1200, equivalent to the European ‘Mediaeval Warm Period,’” and “a period of high effective precipitation followed, from AD 1200 to AD 1700, during the ‘Little Ice Age.’” A moister climate was also inferred during the MWP by Vogel (2003), who upon examining radiocarbon-dated stands of dead *Acacia erioloba* trees from locations within the central Namib Desert concluded trees growing near Sossusvlei (24.75°S, 15.28°E) started growing in the eleventh and twelfth centuries “during the relatively humid conditions of the Medieval Warm Period and died out after the more arid conditions of the Little Ice Age set in during the 14th century.”

Ngomanda *et al.* (2007) derived high-resolution (<40 years) paleoenvironmental reconstructions for the past 1,500 years based on pollen and carbon isotope data obtained from sediment cores retrieved from Lakes Kamalete and Nguene in the lowland rainforest of Gabon. After a sharp rise at ~1200 cal yr BP, the nine researchers note, “A/H [aquatic/

hygrophytic] pollen ratios showed intermediate values and varied strongly from 1150 to 870 cal yr BP, suggesting decadal-scale fluctuations in the water balance during the ‘Medieval Warm Period.’” Thereafter, lower A/H pollen ratios “characterized the interval from ~500 to 300 cal yr BP, indicating lower water levels during the ‘Little Ice Age.’” In addition, they report, “all inferred lake-level low stands, notably between 500 and 300 cal yr BP, are associated with decreases in the score of the TRFO [Tropical Rainforest] biome.”

Ngomanda *et al.* state, “the positive co-variation between lake level and rainforest cover changes may indicate a direct vegetational response to regional precipitation variability,” noting “evergreen rainforest expansion occurs during wet intervals, with contraction during periods of drought.” In this part of Western Equatorial Africa, it appears the Little Ice Age was a time of low precipitation, low lake levels, and low evergreen rainforest presence, while much the opposite was the case during the Medieval Warm Period, when fluctuating wet-dry conditions led to fluctuating lake levels and a greater evergreen rainforest presence.

Placing these findings within a broader temporal context, Ngomanda *et al.* note “rainforest environments during the late Holocene in western equatorial Africa are characterized by successive millennial-scale changes according to pollen (Elenga *et al.*, 1994, 1996; Reynaud-Farrera *et al.*, 1996; Maley and Brenac, 1998; Vincens *et al.*, 1998), diatom (Nguetsop *et al.*, 2004), geochemical (Delegue *et al.*, 2001; Giresse *et al.*, 1994), and sedimentological data (Giresse *et al.*, 2005; Wirmann *et al.*, 2001),” and “these changes were essentially driven by natural climatic variability (Vincens *et al.*, 1999; Elenga *et al.*, 2004).”

Esper *et al.* (2007) used *Cedrus atlantica* ring-width data “to reconstruct long-term changes in the Palmer Drought Severity Index (PDSI) over the past 953 years in Morocco, Northwest Africa.” They report “the long-term PDSI reconstruction indicates generally drier conditions before ~1350, a transition period until ~1450, and generally wetter conditions until the 1970s,” after which there were “dry conditions since the 1980s.” In addition, they determined “the driest 20-year period reconstructed is 1237–1256 (PDSI = -4.2),” adding, “1981–2000 conditions are in line with this historical extreme (-3.9).” Also of significance, the six researchers note “millennium-long temperature reconstructions from Europe (Buntgen *et al.*, 2006) and the Northern

Hemisphere (Esper *et al.*, 2002) indicate that Moroccan drought changes are broadly coherent with well-documented temperature fluctuations including warmth during medieval times, cold in the Little Ice Age, and recent anthropogenic warming.” The latter coherency suggests the peak warmth of the Medieval Warm Period was at least as great as that of the last two decades of the twentieth century throughout the entire Northern Hemisphere. If the coherency is strictly interpreted, it suggests the warmth of the MWP was even greater than that of the late twentieth century.

Working with sediment cores extracted from East Africa’s Lake Tanganyika near the remote and sparsely settled Mahale Mountains (6°33.147’S, 29°58.480’E), Tierney *et al.* (2010) developed a 1,500-year history of lake-surface water temperature (LST) using the TEX86 proxy technique, which relates the degree of cyclization of aquatic archaeal glycerol dialkyl glycerol tetraethers found in membrane lipids of certain marine picoplankton to LST. This work revealed the existence of “a period of extended warmth between AD 1100 and 1400,” which clearly represents the Medieval Warm Period. The peak LST of this period was 1.4°C cooler than the peak LST at the end of the twentieth century.

Kuhnert and Mulitza (2011) derived sea surface temperatures from Mg/Ca ratios of *Globigerinoides ruber* foraminifers extracted from gravity core GeoB 9501-5 recovered off southern Mauritania at 16°50’N, 16°44’W from a water depth of 323 m during Meteor cruise M65/1, described by Mulitza (2006), using the calibration for the 250–350 µm fraction of *G. ruber* (pink) from Anand *et al.* (2003) to produce a 1,700-year summer–fall SST history. Between AD 850 and AD 1150, Kuhnert and Mulitza identify a period of warmth they equate with the Medieval Warm Period, the peak 50-year mean SST of which was 1.1°C greater than the corresponding 50-year mean SST at the end of the record, which had been trending upward over the prior half-century.

The research findings summarized here suggest the Medieval Warm Period occurred over wide reaches of Africa and was probably more extreme in Africa than the Current Warm Period has been to this point in time.

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4.2.4.2 Antarctica

The IPCC has long predicted CO₂-induced global warming, which they assert has accelerated significantly over the twentieth century and is unprecedented in the past millennium or more, should be greatly amplified in Earth's polar regions. The IPCC has claimed the following:

Robust evidence for polar amplification in either one or both hemispheres has been found in climate model experiments of past and future climate change, paleo-climate data and recent instrumental temperature records” (Second Order Draft of AR5, dated October 5, 2012, p. 5–14).

The research reviewed in this section shows the IPCC's claim of “robust evidence” of amplified CO₂-induced warming in Earth's polar regions is patently incorrect, as their thesis has been invalidated by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies of Antarctica demonstrate the atmosphere's CO₂ concentration is not a major player in bringing about significant changes in Earth's climate.

4.2.4.2.1 The Past Few Centuries through the Past Few Millennia

The study of Antarctic temperatures has provided valuable insight into global climate change. Key among early pertinent findings was the observation of a large-scale correlation between proxy air temperature and atmospheric CO₂ measurements obtained from ice cores drilled in the interior of the continent. In the mid- to late-1980s, this broad correlation dominated much of the climate change debate and led many to claim the gross CO₂-temperature correlation proved changes in atmospheric CO₂ concentration caused corresponding changes in air temperature, and future increases in the air's CO₂ content due to anthropogenic CO₂ emissions would therefore intensify global warming.

This contention was challenged by Idso (1989), who wrote in reference to the data used to support the claim, “changes in atmospheric CO₂ content never precede changes in air temperature, when going from glacial to interglacial conditions; and when going from interglacial to glacial conditions, the change in CO₂ concentration actually lags the change in air temperature (Genthon *et al.*, 1987).” He concludes “changes in CO₂ concentration cannot be claimed to be the cause of changes in air temperature, for the appropriate sequence of events (temperature change following CO₂ change) is not only never present, it is actually violated in [at least] half of the record (Idso, 1988).”

Petit *et al.* (1999) reconstructed histories of surface air temperature and atmospheric CO₂ concentration from data obtained from a Vostok ice core that covered the prior 420,000 years, determining “the CO₂ decrease lags the temperature decrease by several thousand years” during glacial inception and “the same sequence of climate forcing operated during each termination.” Fischer *et al.* (1999), working with sections of ice core records from the most recent three glacial terminations, found “the time lag of the rise in CO₂ concentrations with respect to temperature change is on the order of 400 to 1000 years during all three glacial-interglacial transitions.”

By the turn of the century, ice-coring instrumentation and techniques had improved considerably, and newer studies with finer temporal resolution began to reveal increases (decreases) in air temperature drive increases (decreases) in atmospheric CO₂ content and not vice versa, as suggested, for example, by the work of Indermuhle *et al.* (2000) and Monnin *et al.* (2001). A good example

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of this relationship was provided by Caillon *et al.* (2003), who showed during Glacial Termination III “the CO₂ increase lagged Antarctic deglacial warming by 800 ± 200 years.” Although this finding “confirms that CO₂ is not the forcing that initially drives the climatic system during a deglaciation,” they and many others continued to argue the subsequent increase in atmospheric CO₂—believed to be due to warming-induced CO₂ outgassing from the world’s oceans—serves to amplify the warming caused by whatever it is that prompts the temperature to rise in the first place. This conviction, however, is founded on unproven assumptions about the strength of CO₂-induced warming, and it is applied without any regard for biologically induced negative climate feedbacks that can occur in response to atmospheric CO₂ enrichment.

Yoon *et al.* (2002) write, “the maritime record on the Antarctic Peninsula shelf suggests close chronological correlation with Holocene glacial events in the Northern Hemisphere, indicating the possibility of coherent climate variability in the Holocene.” Similarly, Khim *et al.* (2002) state, “two of the most significant climatic events during the late Holocene are the Little Ice Age (LIA) and Medieval Warm Period (MWP), both of which occurred globally (Lamb, 1965; Grove, 1988),” further noting “evidence of the LIA has been found in several studies of Antarctic marine sediments (Leventer and Dunbar, 1988; Leventer *et al.*, 1996; Domack *et al.*, 2000).” Khim *et al.*’s paper can be added to this list of scientific journal articles documenting the existence of the LIA in Antarctica, for it also demonstrates the presence of the MWP in Antarctica, as well as earlier cold and warm periods of similar intensity and duration.

As more studies have been conducted, it has become increasingly clear these several-hundred-year cold and warm periods were not confined to lands bordering the North Atlantic Ocean, as the IPCC suggests. These periods clearly were global, and they demonstrate the reality of the likely solar-induced millennial-scale climatic oscillation that is manifest in the post-1850 warming of the world.

Stenni *et al.* (2002) examined several paleoclimatic indicators in two firn cores retrieved from the Talos Dome area of East Antarctica in 1996, with accurate dating provided by non-sea-salt sulfate spikes associated with well-documented volcanic eruptions and tritium activity associated with known atmospheric thermonuclear bomb tests. The results of their work were compared with those based on other

East Antarctic ice core records obtained from Dome C EPICA, Taylor Dome, and the South Pole. The seven scientists state the several records suggest “cooler climate conditions between the middle of [the] 16th and the beginning of [the] 19th centuries, which might be related to the Little Ice Age (LIA) cold period.” After discussing other findings, they conclude “more and more evidence coming from ice core records, glacier extension and other proxy records are leading to the idea that the Antarctic continent or at least East Antarctica also experienced the LIA cool episode.”

Cremer *et al.* (2003) reconstructed a history of environmental change in the southern Windmill Islands, East Antarctica, based upon diatom assemblages obtained from two long and well-dated sediment cores removed from two marine bays, comparing their findings with those of studies of several other parts of Antarctica. The four researchers note, “the diatom assemblage in the upper sediments of both cores indicates Neoglacial cooling from ~1000 cal yr BP,” and this latest thousand-year period “is generally marked by distinct cooling leading to glacial re-advances, more extensive sea-ice, lower precipitation, and lower bioproductivity.” In addition, they report “this climatic deterioration is visible in nearly all available Antarctic terrestrial and marine records (e.g. Ingolfsson *et al.*, 1998; Jones *et al.*, 2000; Roberts *et al.*, 2000, and references therein).”

Hemer and Harris (2003) extracted a sediment core from beneath the Amery Ice Shelf, East Antarctica, about 80 km landward of its present edge. In analyzing the core’s characteristics over the past 5,700 ¹⁴C years, the two scientists observed a peak in absolute diatom abundance in general, and the abundance of *Fragilariopsis curta* in particular. These parameters, they write, “are associated with increased proximity to an area of primary production, such as the sea-ice zone” at about 750 ¹⁴C yr B.P., which puts the time of maximum Ice Shelf retreat in close proximity to the Medieval Warm Period.

Roberts *et al.* (2004) conducted a fossil diatom analysis of an 82-cm sediment core covering the approximate time period 2,000–1,700 ¹⁴C yr BP, removed from the deepest part of Beall Lake in the northern Windmill Islands in one of the more significant ice-free oases on the East Antarctic coastline. Samples of the core were radiocarbon dated and corrected for the Antarctic reservoir effect. Based on the species of diatoms found in this sample, Roberts *et al.* inferred the existence of a multi-centennial period of warmth characterized by summer

temperatures “much higher than present summer temperatures.” Supporting this inference, they also note observations made at both Casey and Law Dome indicated “during the late Holocene, a warm period existed with precipitation and summer temperatures higher than at present (Goodwin, 1993).” They conclude, “the diatom-inferred Holocene palaeosalinity record from Beall Lake indicates the late Holocene warm period was much warmer than at present.” The dates they give for this period suggest it was part of the Roman Warm Period.

Hall *et al.* (2006) collected skin, hair, and whole-body mummified remains from Holocene raised-beach excavations at locations along Antarctica’s Victoria Land Coast, which they identified by visual inspection and DNA analysis as coming from southern elephant seals (*Mirounga leonina*) and which they analyzed for age by means of radiocarbon dating. Data from 14 locations within the region of study, which they describe as being “well south” of the seals’ current “core sub-Antarctic breeding and molting grounds,” indicate the period of time they denominate the Seal Optimum began about 600 BC and ended about AD 1400, “broadly contemporaneous with the onset of Little Ice Age climatic conditions in the Northern Hemisphere and with glacier advance near [Victoria Land’s] Terra Nova Bay,” although they found evidence of southern elephant seal presence stretching back to the mid-Holocene.

The U.S., British, and Italian researchers say their findings indicate “warmer-than-present climate conditions” at the times and locations of the southern elephant seal presence and “if, as proposed in the literature, the [Ross] ice shelf survived this period, it would have been exposed to environments substantially warmer than present.” Their data also indicate this warmth, which began with the inception of the Roman Warm Period and ended with the demise of the Medieval Warm Period, was so significant that the intervening Dark Ages Cold Period was not intense enough to drive the seals from Antarctica.

Khim *et al.* (2002) analyzed a sediment core removed from the eastern Bransfield Basin just off the northern tip of the Antarctic Peninsula for grain size, total organic carbon content, magnetic susceptibility, biogenic silica content, ^{210}Pb geochronology, and radiocarbon (^{14}C) age. These data clearly depicted the presence of the “Little Ice Age and Medieval Warm period, together with preceding climatic events of similar intensity and duration,”

they write.

Hall *et al.* (2010) write, “over the past 50 years, the Antarctic Peninsula warmed $\sim 2^\circ\text{C}$ ” and resultant rapid ice breakups “have destroyed several small, thin ice shelves fringing the Antarctic Peninsula (i.e., Cook and Vaughan, 2009, and references therein),” leading them to ask, “is the recent warming of the Antarctic Peninsula unique in the Holocene?” The three researchers “examined organic-rich sediments exposed by the recent retreat of the Marr Ice Piedmont on western Anvers Island near Norsel Point,” where glaciers “have been undergoing considerable retreat in response to the well-documented warming.” They “obtained moss and reworked marine shells from natural sections within 26 meters of the present ice front” as well as “both peat and reworked shells from sediments exposed in a tunnel beneath the residual ice mass,” samples of which were radiocarbon-dated and the results converted to calendar years.

The results indicated peat from the overrun sediments dated to between 707 ± 36 and 967 ± 47 cal. yr B.P., which led them to conclude, “ice was at or behind its present position at ca. 700–970 cal. yr B.P. and during at least two earlier times, represented by the dates of shells, in the mid-to-late Holocene.” The three researchers say their findings imply “the present state of reduced ice on the western Antarctic Peninsula is not unprecedented.” This leads them to pose another important question: “How widespread is the event at 700–970 cal. yr B.P.?”

They observe “Khim *et al.* (2002) noted a pronounced high-productivity (warm) event between 500 and 1000 cal. yr B.P. in magnetic susceptibility records from Bransfield Basin” and “dates of moss adjacent to the present ice front in the South Shetland Islands (Hall, 2007) indicate ice there was no more extensive between ca. 650 and 825 cal. yr B.P. than it is now.” They also note “evidence for reduced ice extent at 700–970 cal. yr B.P. is consistent with tree-ring data from New Zealand that show a pronounced peak in summer temperatures (Cook *et al.*, 2002)” and “New Zealand glaciers were retracted at the same time (Schaefer *et al.*, 2009).” They conclude their findings “are compatible with a record of glacier fluctuations from southern South America, the continental landmass closest to Antarctica (Strelin *et al.*, 2008).” It would appear much of the southernmost portion of Earth experienced a period of significantly enhanced warmth within the broad timeframe of the planet’s global MWP.

Lu *et al.* (2012) constructed “the first downcore

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$\delta^{18}\text{O}$ record of natural ikaite hydration waters and crystals collected from the Antarctic Peninsula (AP)” they say were “suitable for reconstructing a low resolution ikaite record of the last 2000 years.” According to the group of nine UK and U.S. researchers, ikaite “is a low temperature polymorph of calcium carbonate that is hydrated with water molecules contained in its crystal lattice,” and they write, “ikaite crystals from marine sediments, if collected and maintained at low temperatures, preserve hydration waters and their intact crystal structures, both of which have the potential to provide isotopic constraints on past climate change.”

Lu *et al.* report “the ikaite record qualitatively supports that both the Medieval Warm Period and Little Ice Age extended to the Antarctic Peninsula.” They also note the “most recent crystals suggest a warming relative to the LIA in the last century, possibly as part of the regional recent rapid warming,” but they add, “this climatic signature is not yet as extreme in nature as the MWP,” suggesting even the recent warming of the AP may not have returned that region to the warmth experienced there during the MWP.

Hall and Denton (2002) mapped the distribution and elevation of surficial deposits along the southern Scott Coast of Antarctica in the vicinity of the Wilson Piedmont Glacier, which runs parallel to the coast of the western Ross Sea from McMurdo Sound north to Granite Harbor. The chronology of the raised beaches they studied was determined from more than 60 ^{14}C dates of incorporated organic materials previously collected from hand-dug excavations (Hall and Denton, 1999). The record shows “the Wilson Piedmont Glacier was still less extensive than it is now” near the end of the Medieval Warm Period, “as late as 890 ^{14}C yr BP.”

Bertler *et al.* (2011) obtained new deuterium (δD) data acquired via analysis of the top 50 meters of a 180-meter-long ice core extracted from the ice divide of Victoria Lower Glacier in the northernmost McMurdo Dry Valleys, which they converted to temperature data by means of a temperature-isotope relationship developed by Steig *et al.* (1998) from data obtained from the Taylor Dome ice core record (see Figure 4.2.4.2.1.1). Bertler *et al.* report they identified three distinct time periods in their record: the last 150 years of the Medieval Warm Period (AD 1140 to 1287), the Little Ice Age (AD 1288 to 1807), and the Modern Era (AD 1808 to 2000). With respect to the Medieval Warm Period, they write, “the McMurdo Dry Valleys were 0.35°C warmer during

the MWP than during ME, accompanied by warmer conditions in the Ross Sea.” The three researchers also note “a magnetic susceptibility record from Palmer Deep marine core (PD92 30MS) also supports warmer MWP conditions, this time in Drake Passage (Domack and Mayewski, 1999).”

Noon *et al.* (2003) used oxygen isotopes preserved in authigenic carbonate retrieved from freshwater sediments of Sombre Lake on Signy Island (60°43’S, 45°38’W) in the Southern Ocean to construct a 7,000-year history of that region’s climate. They found the general trend of temperature at the study site has been downward. Approximately 2,000 years ago, after a thousand-year gap in the data, Signy Island experienced the relative warmth of the last vestiges 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. Then the record shows the Dark Ages Cold period, contemporaneous with what McDermott *et al.* observe in the Northern Hemisphere, after which the Medieval Warm Period appears at the same point in time and persists for the same length of time it does in the vicinity of Ireland, whereupon the Little Ice Age sets in just as it does in the Northern Hemisphere. Finally, there is an indication of late twentieth century warming, still a long way from conditions comparable to those of the Medieval Warm Period (see Figure 4.2.4.2.1.2).

Castellano *et al.* (2005) derived a detailed history of Holocene volcanism from the sulfate record of the first 360 meters of the Dome Concordia ice core that covered the period 0–11.5 kyr BP. They compared their results for the past millennium with similar results obtained from eight other Antarctic ice cores. Before doing so, they normalized the results at each site by dividing its several volcanic-induced sulfate deposition values by the value produced at that site by the AD 1816 Tambora eruption, in order to reduce deposition differences among sites that might have been induced by differences in local site characteristics. This work revealed most volcanic events in the years 1000–1500 AD exhibited greater among-site variability in normalized sulphate deposition than was observed thereafter.

Castellano *et al.* cited Budner and Cole-Dai (2003) in noting “the Antarctic polar vortex is involved in the distribution of stratospheric volcanic aerosols over the continent.” Assuming the intensity and persistence of the polar vortex in both the troposphere and stratosphere “affect the penetration of air masses to inland Antarctica, isolating the

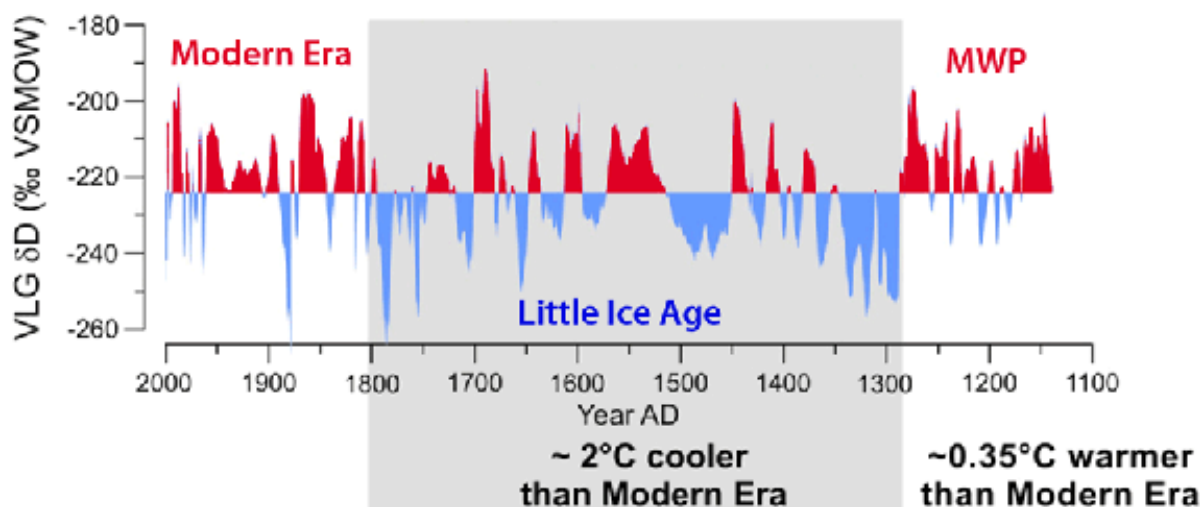


Figure 4.2.4.2.1.1. Deuterium (δD) data acquired from an ice core that had been extracted from the ice divide of Victoria Lower Glacier in the northernmost McMurdo Dry Valleys. Adapted from Bertler, N.A.N., Mayewski, P.A., and Carter, L. 2011. Cold conditions in Antarctica during the Little Ice Age: implications for abrupt climate change mechanisms. *Earth and Planetary Science Letters* **308**: 41–51.

continental area during cold periods and facilitating the advection of peripheral air masses during warm periods (Krinner and Genthon, 1998),” Castellano *et al.* “support the hypothesis that the pattern of volcanic deposition intensity and geographical variability [higher values at coastal sites] could reflect a warmer climate of Antarctica in the early last millennium,” and “the re-establishment of colder conditions, starting in about AD 1500, reduced the variability of volcanic depositions.”

Castellano *et al.* state “this warm/cold step could be like a Medieval Climate Optimum-like to Little Ice Age-like transition.” They additionally cite Goosse *et al.* (2004) as reporting evidence from Antarctic ice-core δD and $\delta^{18}O$ data “in support of a Medieval Warming-like period in the Southern Hemisphere, delayed by about 150 years with respect to Northern Hemisphere Medieval Warming.” The researchers conclude by postulating, “changes in the extent and intra-Antarctic variability of volcanic depositional fluxes may have been consequences of the establishment of a Medieval Warming-like period that lasted until about AD 1500.”

Hall *et al.* (2006) collected skin, hair, and whole-body mummified remains from Holocene raised-beach excavations at locations along Antarctica’s Victoria Land Coast, which they identified by both visual inspection and DNA analysis as coming from southern elephant seals, and which they analyzed for

age by radiocarbon dating. They obtained data from 14 locations within their study region, which they describe as being “well south” of the seals’ current “core sub-Antarctic breeding and molting grounds.” The data indicate the Seal Optimum began about 600 BC and ended about AD 1400; Hall *et al.* describe the latter date as being “broadly contemporaneous with the onset of Little Ice Age climatic conditions in the Northern Hemisphere and with glacier advance near [Victoria Land’s] Terra Nova Bay.” The U.S., British, and Italian researchers say their findings indicate “warmer-than-present climate conditions” at the times and locations of the southern elephant seal presence and “if, as proposed in the literature, the [Ross] ice shelf survived this period, it would have been exposed to environments substantially warmer than present,” which would have included both the Roman Warm Period and Medieval Warm Period.

Williams *et al.* (2007) presented methyl chloride (CH_3Cl) measurements of air extracted from a 300-m ice core obtained at the South Pole, Antarctica, covering the time period 160 BC to AD 1860. The researchers found “ CH_3Cl levels were elevated from 900–1300 AD by about 50 ppt relative to the previous 1000 years, coincident with the warm Medieval Climate Anomaly (MCA),” and they “decreased to a minimum during the Little Ice Age cooling (1650–1800 AD), before rising again to the modern atmospheric level of 550 ppt.” Given that “today,

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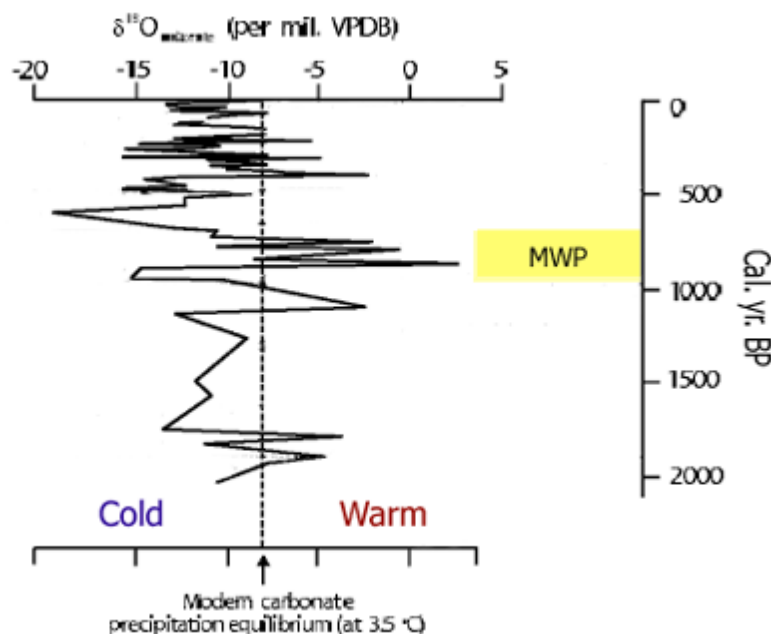


Figure 4.2.4.2.1.2. Sombre Lake $\delta^{18}\text{O}$ record showing the relative warmth of the MWP compared to the CWP. Adapted from Noon, P.E., Leng, M.J., and Jones, V.J. 2003. Oxygen-isotope ($\delta^{18}\text{O}$) evidence of Holocene hydrological changes at Signy Island, maritime Antarctica. *The Holocene* 13: 251–263.

more than 90% of the CH_3Cl sources and the majority of CH_3Cl sinks lie between 30°N and 30°S (Khalil and Rasmussen, 1999; Yoshida *et al.*, 2004),” they conclude “it is likely that climate-controlled variability in CH_3Cl reflects changes in tropical and subtropical conditions.” They state, “ice core CH_3Cl variability over the last two millennia suggests a positive relationship between atmospheric CH_3Cl and global mean temperature.”

As best as can be determined from the graphical representation of their data, the peak CH_3Cl concentration measured by Williams *et al.* during the MCA is approximately 533 ppt, which is within 3 percent of its current mean value of 550 ppt and well within the range of 520 to 580 ppt that characterizes methyl chloride’s current variability. It therefore may be validly concluded the mean peak temperature of the MCA (Medieval Warm Period) over the latitude range 30°N to 30°S —and possibly over the entire globe—may not have been materially different from the mean peak temperature so far attained during the Current Warm Period.

Hall (2007) presented “radiocarbon and geomorphologic data that constrain [the] late-Holocene extent of the Collins Ice Cap on Fildes Peninsula (King George Island, South Shetland

Islands: $62^\circ 10' 51''\text{S}$, $58^\circ 54' 13''\text{W}$),” which “yield information on times in the past when climate in the South Shetland Islands must have been as warm as or warmer than today,” based on field mapping of moraines and glacial deposits adjacent to the ice cap as well as radiocarbon dates of associated organic materials. Such data, Hall writes, “indicate ice advance after ~ 650 cal. yr BP (AD ~ 1300),” which she notes is “broadly contemporaneous with the ‘Little Ice Age’, as defined in Europe.” She also says this was “the only advance that extended beyond the present ice margin in the last 3500 years, making the Little Ice Age in that part of the world likely the coldest period of the current interglacial. And since “the

present ice cap margin ... is still more extensive than it was prior to ~ 650 cal. yr BP” she concludes the climate prior to that time, which would have comprised the Medieval Warm Period, may have been “as warm as or warmer than present.”

Working with an ice core (IND-22/B4) extracted during the austral summer of 2003 from the coastal region of Dronning Maud Land, East Antarctica ($70^\circ 51.3'\text{S}$, $11^\circ 32.2'\text{E}$) as part of the 22nd Indian Antarctic Expedition, Thamban *et al.* (2011) developed 470-year histories of $\delta^{18}\text{O}$ and δD that “showed similar down core fluctuations with [an] excellent positive relationship ($R^2 = 0.9$; $n = 216$) between the two.” Based on a $\delta^{18}\text{O}$ vs. surface air temperature (SAT) relationship developed for this region by Naik *et al.* (2001), they derived the regional temperature history depicted in Figure 4.2.4.2.1.3.

In describing the temperature history, the four Indian researchers state, “the estimated surface air temperature at the core site revealed a significant warming of 2.7°C with a warming of $\sim 0.6^\circ\text{C}$ per century for the past 470 years,” not surprising given that the starting point for this record is the depth of the Little Ice Age. While the record shows decadal fluctuations, there has been no net warming for the entire twentieth century, with the warmest

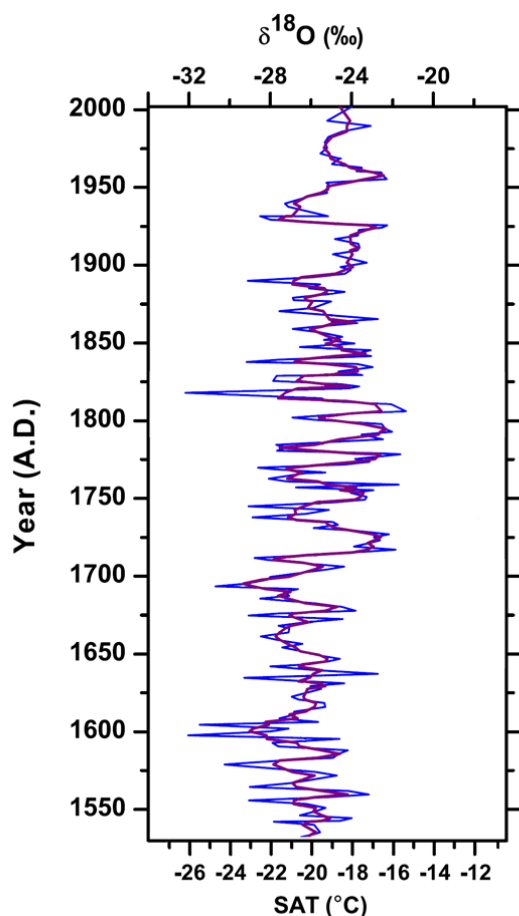


Figure 4.2.4.2.1.3. Surface air temperature (SAT) as derived from $\delta^{18}\text{O}$ data vs. time in years AD. Adapted from Thamban, M., Laluraj, C.M., Naik, S.S., and Chaturvedi, A. 2011. Reconstruction of Antarctic climate change using ice core proxy records from coastal Dronning Maud Land, East Antarctica. *Journal of the Geological Society of India* **78**: 19–29.

temperatures of the century occurring around 1925 and 1960.

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4.2.4.2.2 The Past One to Two Centuries

Another significant impediment to the CO₂-induced global warming hypothesis comes from the instrumental temperature record of the more recent past. According to nearly all climate models, CO₂-induced global warming should be most evident in Earth's polar regions, but analyses of Antarctic near-surface and tropospheric air temperature records tell a

radically different story.

Doran *et al.* (2002) examined temperature trends in the McMurdo Dry Valleys of Antarctica over the period 1986 to 2000, reporting a cooling rate of approximately 0.7°C per decade. This dramatic rate of cooling “reflects longer term continental Antarctic cooling between 1966 and 2000.” In addition, the 14-year temperature decline in the dry valleys occurred in the summer and autumn, as did most of the 35-year cooling over the continent as a whole exclusive of the dry valley data.

Comiso (2000) assembled and analyzed Antarctic temperature data from 21 surface stations and from infrared satellites operating since 1979, finding for all of Antarctica, temperatures declined by 0.08°C and 0.42°C per decade, respectively. Thompson and Solomon (2002) also report a cooling trend for the interior of Antarctica.

In spite of the decades-long cooling observed for the continent as a whole, one region of Antarctica has warmed over the same time period: the Antarctic Peninsula/Bellingshausen Sea region. But the temperature increase there is not evidence of CO₂-induced global warming.

According to Vaughan *et al.* (2001), “rapid regional warming” has led during the past 50 years to the loss of seven ice shelves, including the Prince Gustav Channel Ice Shelf, which collapsed in this region in 1995. However, they note sediment cores from 6,000 to 1,900 years ago suggest the Prince Gustav Channel Ice Shelf “was absent then and climate was as warm as it has been recently,” although there was much less CO₂ in the air than there is today. Vaughan *et al.* say it “is superficial” to cite the twentieth century increase in atmospheric CO₂ concentration as the cause of the recent regional warming without providing an explanatory mechanism.

Thompson and Solomon (2002) suggest much of the warming can be explained by “a systematic bias toward the high-index polarity of the SAM,” or Southern Hemispheric Annular Mode, such that the ring of westerly winds encircling Antarctica has recently been spending more time in its strong-wind phase. A similar conclusion was reached by Kwok and Comiso (2002), who report over the 17-year period 1982–1998 the SAM index shifted towards more positive values (0.22/decade). They also note a positive polarity of the SAM index “is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau.” At the same time, the Southern Oscillation (SO) index

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shifted in a negative direction, indicating “a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over much of the continent.”

Thus Kwok and Comiso conclude the positive trend in the coupled mode of variability of these two indices represents a “significant bias toward positive polarity.” Also, the SAM “has been shown to be related to changes in the lower stratosphere (Thompson and Wallace, 2000)” and “the high index polarity of the SAM is associated with the trend toward a cooling and strengthening of the Southern Hemisphere stratospheric polar vortex during the stratosphere’s relatively short active season in November,” as Thompson and Solomon (2002) hypothesized.

Mulvaney *et al.* (2012) drilled an ice core to the bed of the ice cap on James Ross Island, which lies just off the northeastern tip of the Antarctic Peninsula, next to an area that has experienced a series of recent ice-shelf collapses. Based on deuterium/hydrogen isotope ratios of the ice (δD), they developed a temperature history of the region that spans the entire Holocene and extends into the last glacial period. They found “the Antarctic Peninsula experienced an early Holocene warm period followed by stable temperatures, from about 9200 to 2500 years ago, that were 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, they state, “over the past 100 years, the James Ross Island ice-core record shows that the mean temperature there has increased by $1.56 \pm 0.42^\circ\text{C}$,” which ranks as one of the fastest (upper 0.3%) warming trends since 2,000 years before present, according to a set of moving 100-year analyses that demonstrate “rapid recent warming of the Antarctic Peninsula is highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era.” Although the temperature of the northern Antarctic Peninsula has risen at a rate of $2.6 \pm 1.2^\circ\text{C}$ over the past half-century, they state, “repeating the temperature trend analysis using 50-year windows confirms the finding that the rapidity of recent Antarctic Peninsula warming is unusual but not unprecedented.”

Watkins and Simmonds (2000), who analyzed region-wide changes in sea ice, suggest Antarctica as a whole appears to be experiencing a cooling trend. Reporting on trends in several Southern Ocean sea ice parameters over the period 1987 to 1996, they found

statistically significant increases in sea ice area and total sea ice extent, as well as an increase in sea ice season length since the 1990s. Combining these results with those from a previous study revealed the trends to be consistent back to at least 1978. And in another study of Antarctic sea ice extent, Yuan and Martinson (2000) report the net trend in the mean Antarctic ice edge over the past 18 years has been an equator-ward expansion of 0.011 degree of latitude per year.

Liu *et al.* (2004) used sea ice concentration data retrieved from the scanning multi-channel 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 covering an entire 22-year solar cycle (1979–2002) that included different states of the Antarctic Oscillation and several ENSO events. They then evaluated total sea ice extent and area trends by means of linear least-squares regression. They report, “overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend ($\sim 4,801 \text{ km}^2/\text{yr}$).” In addition, they determined “the total Antarctic sea ice area (the cumulative area of the ocean actually covered by at least 15% ice concentrations) has increased significantly by $\sim 13,295 \text{ km}^2/\text{yr}$, exceeding the 95% confidence level,” while noting “the upward trends in the total ice extent and area are robust for different cutoffs of 15, 20, and 30% ice concentrations (used to define the ice extent and area).”

Turner *et al.* (2005) used a “new and improved” set of Antarctic climate data, described in detail by Turner *et al.* (2004), to examine “the temporal variability and change in some of the key meteorological parameters at Antarctic stations.” This revealed a warming at low elevations on the western coast of the Antarctic Peninsula, which they describe as being “as large as any increase observed on Earth over the last 50 years,” and which at the Faraday (now Vernadsky) station was about 2.5°C . However, they note the “region of marked warming is quite limited and is restricted to an arc from the southwestern part of the peninsula, through Faraday to a little beyond the tip of the peninsula.”

Outside the Antarctic Peninsula, they report “there has been a broad-scale change in the nature of the temperature trends between 1961–90 and 1971–2000.” Specifically, of the ten coastal stations that have long enough records to allow 30-year

temperature trends to be computed for both of these periods, “eight had a larger warming trend (or a smaller cooling trend) in the earlier period.” Four changed from warming to cooling, as did the interior Vostok site, and at the South Pole the rate of cooling intensified by a factor of six. Thus, over the latter part of the twentieth century—during which the IPCC claims to have found the most dramatic global warming of the past two millennia—fully 80 percent of the Antarctic coastal stations with sufficiently long temperature records revealed either an intensification of cooling or a reduced rate of warming, while four coastal sites and one interior site shifted from warming to cooling. All of this occurred in one of the planet’s high-latitude polar regions, where CO₂-induced global warming has been predicted to be more strongly expressed than any other place on the planet.

Schneider *et al.* (2006) utilized 200 years of sub-annually resolved $\delta^{18}\text{O}$ and δD records from precisely dated ice cores obtained from Law Dome, Siple Station, Dronning Maud Land and two West Antarctic sites of the United States component of the International Trans-Antarctic Scientific Expedition to create a 200-year-long Antarctic temperature reconstruction representing the main part of the continent. The results of this undertaking, after application of a multi-decadal low-pass filter to the yearly data, are illustrated in Figure 4.2.4.2.2.1, along with the similarly treated data of the Southern Hemisphere instrumental temperature record, where the zero line represents the 1961–1990 climatological means of the two records.

Schneider *et al.* say “it is notable that the reconstructed Antarctic temperature record is in phase with the Southern Hemisphere mean instrumental record.” This statement roughly describes the relationship between the two histories, but only until 1990, after which the Antarctic temperature history dramatically diverges from the Southern Hemisphere record. The seven scientists also state the Antarctic temperature reconstruction “provides evidence for long-term Antarctic warming,” and if all the data they had were those that stretch from 1840 to 1990, they would be correct. However, when their “before and after” data are included, this statement is readily seen to be incorrect.

Schneider *et al.*’s data suggest there was nothing unusual, unnatural, or unprecedented about any

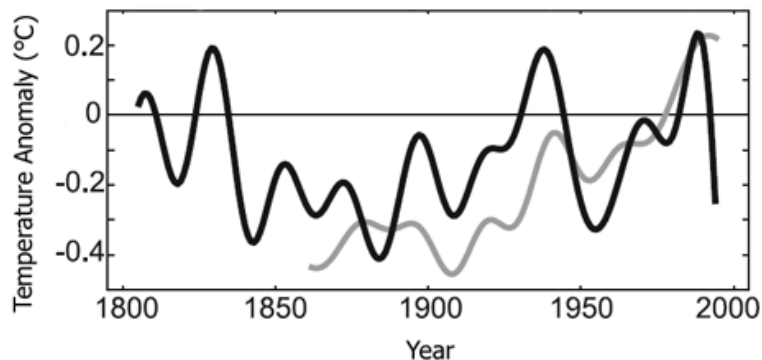


Figure 4.2.4.2.2.1. Mean temperature histories of Antarctica (dark line) and the Southern Hemisphere (lighter line), adapted from the paper of Schneider, D.P., Steig, E.J., van Ommen, T.D., Dixon, D.A., Mayewski, P.A., Jones, J.M., and Bitz, C.M. 2006. Antarctic temperatures over the past two centuries from ice cores. *Geophysical Research Letters* **33**: 10.1029/2006GL027057.

Antarctic temperatures of any part of the twentieth century. Their data also demonstrate it was significantly colder in Antarctica near the end of the twentieth century than in the early decades of the nineteenth century, when the air’s CO₂ concentration was about 100 ppm less than it is today, while data compiled by others indicates it may be even colder there today.

Chapman and Walsh (2007) used monthly surface air temperatures from manned and automatic weather stations along with ship/buoy observations from the high-latitude Southern Hemisphere to develop a gridded database with resolution appropriate for applications ranging from spatial trend analyses to climate change impact assessments. These data came from 460 locations in the Southern Hemisphere, where temperatures over land were obtained from 19 manned stations of the World Monthly Surface Station Climatology network, most of which were located in coastal areas of the Antarctic continent, plus 73 stations of the Automated Weather Station network, many of which were situated further inland. Temperatures over the sea were obtained from the International Comprehensive Ocean-Atmosphere Data repository. The two researchers used correlation length scaling “to enhance information content while limiting the spatial extent of influence of the sparse data in the Antarctic region.”

The final results of Chapman and Walsh’s efforts in this regard are presented in Figure 4.2.4.2.2.2. This figure clearly shows a post-1958 warming of Antarctica and much of the surrounding Southern

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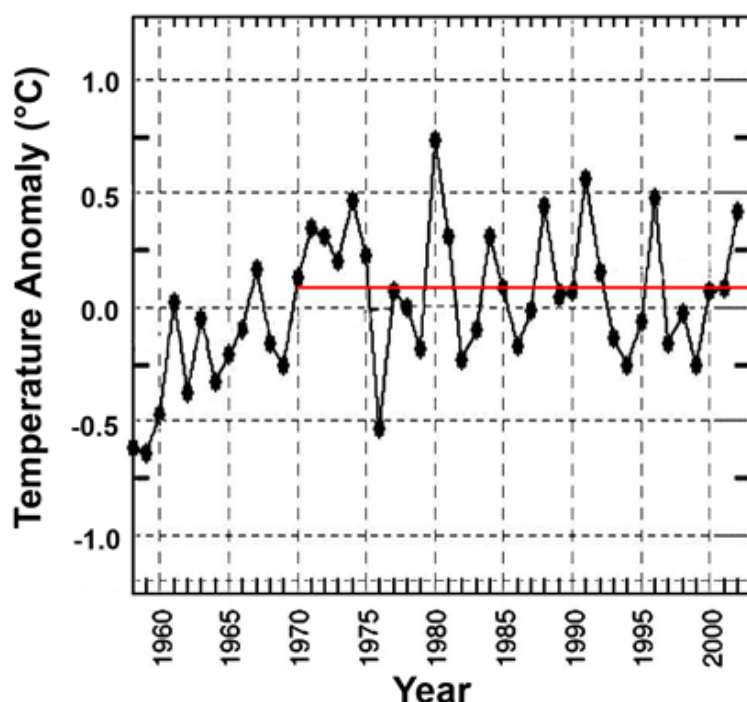


Figure 4.2.4.2.2.2. Annual surface air temperature anomalies relative to the 1958–2002 mean for the region of the Southern Hemisphere extending from 60 to 90°S. Adapted from Chapman, W.L. and Walsh, J.E. 2007. A synthesis of Antarctic temperatures. *Journal of Climate* **20**: 4096–4117.

Ocean. From approximately 1970 to the end of the record, however, temperatures of the region simply fluctuated around an anomaly mean of about 0.12°C, neither warming nor cooling. This is rather surprising in light of the fact that the region of study includes the Antarctic Peninsula, which experienced phenomenal warming during this period. Nevertheless, the mean surface air temperature of the entire region changed not at all, over a period of time that saw the air's CO₂ concentration rise by approximately 47 ppm, about 15 percent of its 1970 value, as per the Mauna Loa CO₂ record. Clearly, the continent of Antarctica, together with much of the Southern Ocean that surrounds it, has been unaffected by the warming supposedly produced by anthropogenic emissions of CO₂ and other greenhouse gases over the last three decades of the twentieth century.

Concentrating on the spring–summer period of November/December/January, Laine (2008) determined 1981–2000 trends of Antarctic ice-sheet and sea-ice surface albedo and temperature, as well as sea-ice concentration and extent, based on Advanced Very High Resolution Polar Pathfinder data in the case of ice-sheet surface albedo and temperature, and

the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave Imagers in the case of sea-ice concentration and extent. These analyses were carried out for the continent as a whole and for five longitudinal sectors emanating from the South Pole: 20°E–90°E, 90°E–160°E, 160°E–130°W, 130°W–60°W, and 60°W–20°E.

Laine found “all the regions show negative spring–summer surface temperature trends for the study period” and “the slight cooling trends seem to be parallel with the results of Comiso (2000), who studied Antarctic temperature trends using both satellite and station data.” In addition, the Finnish researcher states, “the 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.”

Monaghan and Bromwich (2008) reviewed what has been learned about snowfall and near-surface air temperature over the past five decades in Antarctica. They point out, “snowfall is the largest contributor to the growth of the ice sheets, and near-surface temperature controls surface melting, which in turn has important impacts on the stability of Antarctic ice shelves and glaciers,” which ultimately impact global sea level.

The two researchers from the Byrd Polar Research Center of Ohio State University (USA) first note “instrumental records indicate statistically insignificant seasonal and annual near-surface temperature changes over continental Antarctica from the late 1950s through 2000,” citing the work of Turner *et al.* (2005). On the Antarctic Peninsula, by contrast, temperature measured at the Faraday/Vernadsky station rose at the phenomenal rate of 0.56°C per decade from 1951 to 2000. But the peninsula comprises a mere 4 percent of the continent's total surface area, and its warming, although dramatic, is only a small-scale anomaly.

In describing another study of the temperature history of Antarctica, Monaghan and Bromwich report, “Chapman and Walsh (2007) performed an objective analysis of Antarctic near-surface temperatures from the early 1950s through 2002 and found the overall Antarctic temperature trends depend

on the period for which they are calculated, being positive prior to 1965 (through 2002), and mainly negative thereafter, although never statistically significant for any period.” Similarly, after citing the work of Kwok and Comiso (2002) with skin temperature records derived from Advanced Very High Resolution Radiometer instrumentation flown aboard polar-orbiting satellites, the work of Schneider *et al.* (2006) with temperatures derived from ice-core stable isotopes, and the work of Monaghan *et al.* (2008) that blended the instrumental temperature record with model reanalysis temperature fields, Monaghan and Bromwich conclude, “overall there have not been statistically significant Antarctic near-surface temperature trends since the International Geophysical Year” of 1957–1958.

Turning their attention to snowfall, Monaghan and Bromwich note “atmospheric models have been the primary tool for assessing temporal variability,” and they report the latest such studies of Antarctic snowfall “indicate that no statistically significant increase has occurred since ~1980,” citing the analyses of Monaghan *et al.* (2006) and van de Berg *et al.* (2005), although there have been cyclical changes related to similar changes in temperature. When the two variations are compared on decadal time scales, it appears snowfall over Antarctica could rise by as much as 5 percent for each 1°C increase in temperature.

As to what the future might hold for Antarctic snowfall in a warming world, the two researchers state, “if global climate model projections of 2–3.5°C temperature increases over Antarctica by the end of this century are accurate”—which is highly debatable—“a ~10%–20% increase in snowfall might be expected if the 1960–2004 sensitivity relationship holds.” They note “a 15% increase of Antarctic snowfall would mitigate an additional ~1 mm per year [rise] of global sea level in 2100 compared to today.” Thus the rise in sea level predicted by the IPCC to occur this century appears to be highly unlikely, especially in light of Monaghan and Bromwich’s ultimate observation that “a widespread signal of Antarctic climate change is not obvious over the past ~50 years.”

Sinclair *et al.* (2012) write, “although the Antarctic ice sheet plays a pivotal role in the global ocean and atmospheric circulation systems and their response to warming climates, there are few long-term observations of surface temperature across the continent,” which they say is “particularly true for areas pole-ward of the Antarctic Peninsula because of

the sparsity of scientific bases and problems associated with satellite measurements of surface temperature (Mayewski *et al.*, 2009).” Consequently, they assert there is a “pressing need for a better understanding of climate variability and the forcings that underlie these changes.”

Thus Sinclair *et al.* studied isotope-temperature relationships at a site on the Whitehall Glacier in northern Victoria Land (72°54’S, 169°5’E) on a flat ice divide about 12 km from the nearest seasonally open water. Working with an ice core drilled to a depth of 105 meters there in 2006/2007, they developed a well-calibrated isotope-temperature relationship and used it to reconstruct annual temperatures, as well as summer (December–February) and cold season (April–September) temperatures, for the 125-year span of their data. Over the full length of their record, the three researchers state, they could find “no significant [temperature] trends between 1882 and 2006.” Neither were there any significant trends in either summer or cold season temperatures since 1958. However, they report “a decrease in cold season temperatures of $-1.59^{\circ}\text{C} \pm 0.84^{\circ}\text{C/decade}$ at 90% confidence ($p = 0.07$) since 1979,” and this cooling was “coincident with a positive trend in the southern annular mode, which is linked to stronger southerly winds and increased sea ice extent and duration in the western Ross Sea,” which they say “is one of the few regions experiencing a significant positive trend in sea ice and a negative trend in sea surface temperatures,” citing Comiso *et al.* (2011).

It is clear the temperature history of Antarctica provides no evidence for the CO₂-induced global warming hypothesis and in fact argues strongly against it.

And even if the Antarctic were to warm as a result of some natural or anthropogenic-induced change in Earth’s climate, the consequences likely would not be grave. Both the number and diversity of penguin species (Smith *et al.*, 1999; Sun *et al.*, 2000) likely would improve, as would the size and number of the continent’s only two vascular plant species (Xiong *et al.*, 2000). The great ice sheets likely would survive, as not even a warming event as dramatic as 10°C is predicted to result in a net change in the East Antarctic Ice Sheet (Näslund *et al.*, 2000), which suggests predictions of catastrophic coastal flooding due to melting from the world’s polar ice sheets are off the mark.

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4.2.4.3 Arctic

The IPCC has long predicted CO₂-induced global warming—which they assert has accelerated significantly during the twentieth century and is unprecedented in the past millennium or more—should be greatly amplified in Earth’s polar regions:

Robust evidence for polar amplification in either one or both hemispheres has been found in climate model experiments of past and future climate change, paleo-climate data and recent instrumental temperature records (Second Order Draft of AR5, dated October 5, 2012, p. 5-14).

As shown in the subsections below, the IPCC’s claim of “robust evidence” of amplified CO₂-induced warming in Earth’s polar regions is patently false, having been invalidated time and again by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies of the Arctic’s climate show the atmosphere’s CO₂ concentration is not a major player in bringing about significant changes in Earth’s climate. In the following sections, we present brief reviews of pertinent studies of glacial periods, the Holocene, and the past few decades.

4.2.4.3.1 The Past Several Interglacial Cycles

Beginning with the current interglacial or Holocene, Darby *et al.* (2001) developed a 10,000-year multi-parameter environmental record from a thick sequence of post-glacial sediments obtained from cores extracted from the upper continental slope off the Chukchi Sea Shelf in the Arctic Ocean. They uncovered evidence that revealed “previously unrecognized millennial-scale variability in Arctic Ocean circulation and climate,” along with evidence suggesting “in the recent past, the western Arctic

Ocean was much warmer than it is today.” They state, “during the middle Holocene the August sea surface temperature fluctuated by 5°C and was 3–7°C warmer than it is today,” and they report their data revealed “rapid and large (1–2°C) shifts in bottom water temperature.” They conclude, “Holocene variability in the western Arctic is larger than any change observed in this area over the last century.”

Miller *et al.* (2005) summarize the main characteristics of the glacial and climatic history of the Canadian Arctic’s Baffin Island since the Last Glacial Maximum by presenting biotic and physical proxy climate data derived from six lacustrine sediment cores recovered from four sites on Baffin Island. The paleoenvironmental implications of the new data were combined with the findings of prior studies to develop a regional picture of climatic conditions during deglaciation, the subsequent Holocene thermal maximum, the onset of Neoglaciation and its intensification in the late Holocene. This work revealed “glaciers throughout the Canadian Arctic show clear evidence of Little Ice Age expansion, persisting until the late 1800s, followed by variable recession over the past century.” Wherever the Little Ice Age advance can be compared to earlier advances, they note, “the Little Ice Age is the most extensive Late Holocene advance” and “some glaciers remain at their Little Ice Age maximum.” Because the Little Ice Age in the Canadian Arctic spawned the region’s most extensive glacial advances of the entire Holocene, and because many of the resulting glaciers persisted into the late 1800s, with some remaining at their maximum Little Ice Age extensions, it is only to be expected the region would experience a significant warming as the planet recovers from this coldest phase of the Holocene, independent of the air’s CO₂ concentration.

Frechette *et al.* (2006) employed radiocarbon and luminescence dating of macrofossils contained in sediment cores recovered from three mid-Arctic lakes on the Cumberland Peninsula of eastern Baffin Island in the Canadian Arctic to isolate and study the portions of the cores pertaining to the interglacial that preceded the Holocene, which occurred approximately 117,000–130,000 years ago. They reconstructed the past vegetation and climate of the region during this period based on pollen spectra derived from the cores. “In each core,” they write, “last interglacial sediments yielded remarkably high pollen concentrations, and included far greater percentages of shrub (*Betula* and *Alnus*) pollen grains than did overlying Holocene sediments.” Also, “from

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applications of both correspondence analysis regression and best modern analogue methodologies, we infer July air temperatures of the last interglacial to have been 4 to 5°C warmer than present on eastern Baffin Island,” greater warmth than in any interval within the Holocene. They say their temperature reconstruction is “directly comparable to both earlier qualitative estimates (LIGA Members, 1991; Bennike and Bocher, 1994), as well as more recent quantifications from ice core (NGRIP Members, 2004) and pollen (Andreev *et al.*, 2004) analyses.”

In a companion study, Francis *et al.* (2006) analyzed midge remains found in cores recovered from two of the same Baffin Island lakes (Fog Lake and Brother of Fog Lake) for which Frechette *et al.* analyzed pollen spectra, reconstructing lake water temperatures and mean July air temperatures for the Holocene and the prior interglacial period. They write, “reconstructions at both [lake] sites indicate that summer temperatures during the last interglacial were higher than at any time in the Holocene, and 5 to 10°C higher than present.”

The 25 authors of a major review paper (CAPE-Last Interglacial Project Members, 2006) present “quantitative estimates of circum-Arctic Last Interglaciation (LIG) summer air and sea-surface temperatures reconstructed from proxy records preserved in terrestrial and marine archives,” including beach morphology, beetles, benthic foraminifera, chironomids, coccoliths, δD , $\delta^{18}O$, dinocysts, insects, invertebrates, Mg/Ca ratio, mollusks, nanofossils, needles, ostracodes, planktic foraminifera, plant microfossils, pollen, soils, spores, tephra, and treeline position. They report, “quantitative reconstructions of LIG summer temperatures suggest that much of the Arctic was 5°C warmer during the LIG than at present.” With respect to the impacts of this warmth, they state Arctic summers of the LIG “were warm enough to melt all glaciers below 5 km elevation except the Greenland Ice Sheet, which was reduced by ca 20–50% (Cuffey and Marshall, 2000; Otto-Bliesner *et al.*, 2006).” In addition, they note, “the margins of permanent Arctic Ocean sea ice retracted well into the Arctic Ocean basin and boreal forests advanced to the Arctic Ocean coast across vast regions of the Arctic currently occupied by tundra.”

Clearly, if there is anything strange or unusual about current Arctic temperatures it is that they are so much lower than they were during the maximum warmth of the current interglacial and, even more so, the prior interglacial. If the Arctic behaves anything

like the Antarctic in this regard, one can extend this comparison back in time through three more interglacials, all of which were also warmer than the current one (Petit *et al.*, 1999; Augustin *et al.*, 2004).

White *et al.* (2010) produced a comprehensive review of past climate change in Earth’s north polar region. The nine researchers describe how “processes linked with continental drift have affected atmospheric circulation, ocean currents, and the composition of the atmosphere over tens of millions of years,” and “a global cooling trend over the last 60 million years has altered conditions near sea level in the Arctic from ice-free year-round to completely ice covered.” They also report, “variations in arctic insolation over tens of thousands of years in response to orbital forcing have caused regular cycles of warming and cooling that were roughly half the size of the continental-drift-linked changes,” and, in turn, this glacial-interglacial cycling “was punctuated by abrupt millennial oscillations, which near the North Atlantic were roughly half as large as the glacial-interglacial cycles.” They also note “the current interglacial, the Holocene, has been influenced by brief cooling events from single volcanic eruptions, slower but longer lasting changes from random fluctuations in the frequency of volcanic eruptions, from weak solar variability, and perhaps by other classes of events.”

White *et al.* conclude “thus far, human influence does not stand out relative to other, natural causes of climate change.” They say the data “clearly show” that “strong natural variability has been characteristic of the Arctic at all time scales considered” and “the human influence on rate and size of climate change thus far does not stand out strongly from other causes of climate change.”

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4.2.4.3.2 The Past Few Centuries through the Past Few Millennia

The IPCC contends current temperatures are both unnatural and unprecedented, a result of global warming caused by anthropogenic CO₂ emissions, and they claim this “unnaturalness” is most strongly expressed in the world’s Arctic regions. This section investigates that claim in the context of the latter part of the current interglacial or Holocene, based on studies conducted in the Arctic.

The Arctic—which climate models suggest should be sensitive to greenhouse-gas-induced warming—is still not as warm as it was many centuries ago, especially during portions of the Medieval Warm Period, when there was much less CO₂ and methane in the air than there is today. This further suggests there is no compelling reason to conclude, as does the IPCC, that the twentieth century increase in the air’s CO₂ content (a 120ppm rise above what it was during the warmer Medieval Warm Period) was the cause of twentieth century warming, especially when it is claimed such warming should be most evident and earliest expressed in high northern latitudes, and in light of the millennial-scale climatic cycle that alternately brings the Earth relatively warmer and cooler century-scale conditions throughout both glacial and interglacial periods alike.

4.2.4.3.2.1 Canada

Moore *et al.* (2001) analyzed sediment cores extracted from Donard Lake, Baffin Island, Canada (~66.25°N, 62°W), to produce a 1,240-year record of mean summer temperature for this region that averaged 2.9°C over the period AD 750–1990 (see Figure 4.2.4.3.2.1.1). Within this period there were several anomalously warm decades with temperatures as high as 4°C around AD 1000 and 1100, and at the beginning of the thirteenth century Donard Lake

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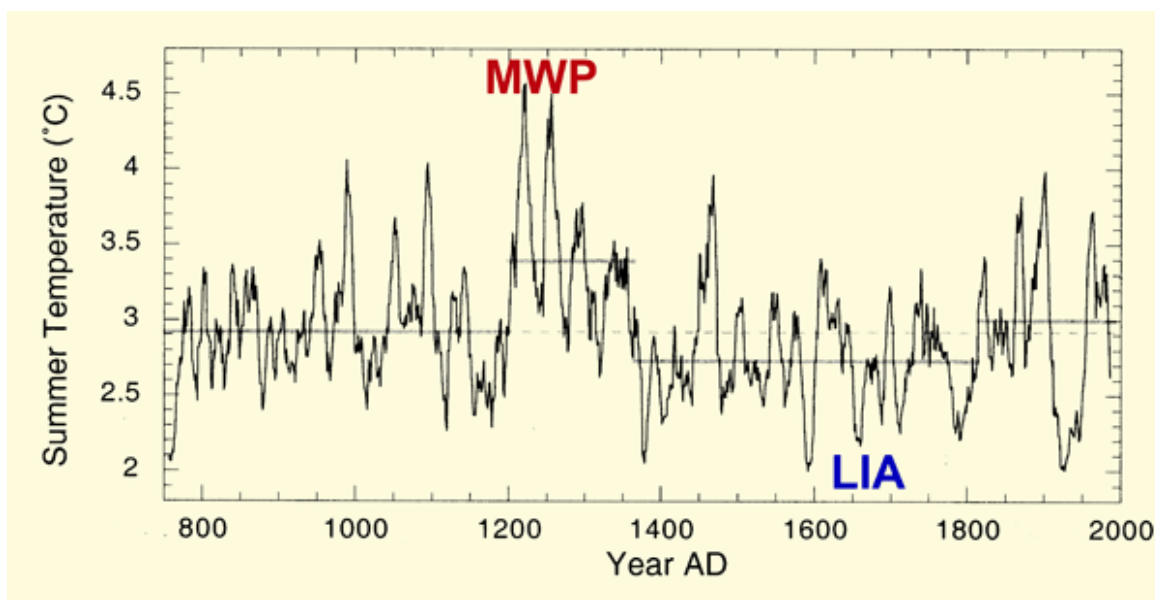


Figure 4.2.4.3.2.1.1. A 1,240-year proxy record of mean summer temperature from sediment cores extracted from Donard Lake, Baffin Island, Canada. Adapted from Moore, J.J., Hughen, K.A., Miller, G.H., and Overpeck, J.T. 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. *Journal of Paleolimnology* **25**: 503–517.

witnessed what Moore *et al.* called “one of the largest climatic transitions in over a millennium,” as “average summer temperatures rose rapidly by nearly 2°C from AD 1195–1220, ending in the warmest decade in the record,” with temperatures near 4.5°C. That temperature rise was followed by a period of extended warmth that lasted until an abrupt cooling event occurred around AD 1375, resulting in the following decade being one of the coldest in the record and signaling the onset of the Little Ice Age on Baffin Island, which lasted for 400 years.

At the modern end of the record, a gradual warming trend occurred over the period 1800–1900, followed by a dramatic cooling event that brought temperatures back down to levels characteristic of the Little Ice Age, which lasted until about 1950. Thereafter, temperatures rose once more throughout the 1950s and 1960s, whereupon they trended downward toward cooler conditions to the end of the record in 1990.

Kasper and Allard (2001) examined soil deformations caused by ice wedges, a widespread and abundant form of ground ice in permafrost regions that can grow during colder periods and deform and crack the soil. Working near Salluit, northern Québec (approx. 62°N, 75.75°W), they found evidence of ice wedge activity prior to AD 140, reflecting cold

climatic conditions. Between AD 140 and 1030 this activity decreased, indicating warmer conditions. From AD 1030 to 1500 conditions cooled, and from 1500 to 1900 ice wedge activity was at its peak, when the Little Ice Age ruled, suggesting this climatic interval exhibited the coldest conditions of the past 4,000 years. Thereafter, a warmer period prevailed from about 1900 to 1946, followed by a return to cold conditions during the last five decades of the twentieth century, during which more than 90 percent of the ice wedges studied reactivated and grew by 20–30 cm, in harmony with a reported temperature decline of 1.1°C observed at the meteorological station in Salluit. This cooling is vastly different from the “unprecedented warming” the IPCC contends was occurring during this same period of time.

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. Citing seven other studies, they write, “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 reveal “the twelfth and thirteenth centuries were relatively warm” and often much warmer during this time period (AD 1080–1320) than at any point in the twentieth century.

Cook *et al.* (2009) examined sediment cores extracted from Lower Murray Lake in 2005 and 2006 to calculate annual mass accumulation rate (MAR) for the past five millennia, which they used to derive a relationship between MAR and July temperature at the two nearest permanent weather stations over the period of instrumental measurements. This revealed several periods over the past 5,000 years when the temperature of the region exceeded the peak temperature of the twentieth century, the most recent of which was during the Medieval Warm Period, delineated in Figure 4.2.4.3.2.1.2 as occurring between about AD 930 and 1400. The peak temperature of that period can be seen to have been about 0.6°C higher than the peak temperature of the Current Warm Period.

Vare *et al.* (2009) used a novel biomarker (IP25), which they describe as a mono-unsaturated highly branched isoprenoid synthesized by sea ice diatoms that have been shown to be stable in sediments below Arctic sea ice, together with “proxy data obtained from analysis of other organic biomarkers, stable isotope composition of bulk organic matter, benthic foraminifera, particle size distributions and ratios of inorganic elements,” to develop a spring sea ice record for the central Canadian Arctic Archipelago. They discovered evidence for a decrease in spring sea ice between approximately 1,200 and 800 years before present (BP), which they associate with “the so-called Mediaeval Warm Period.”

Fortin and Gajewski (2010) developed an 8,000-year history of mean July air temperature in the Wynniatt Bay region of Canada’s Northern Victoria Island (72.29°N, 109.87°W) using two replicate sediment cores extracted from the central point of Lake WB02 in June 1997. They employed the modern analogue technique (MAT) and weighted averaging partial least squares (WAPLS) regression, utilizing chironomid species assemblage data. As best as can be determined from their graphical results, late-Holocene temperatures peaked about 1,100 years ago in both reconstructions, at values approximately 3.8°C warmer than the peak temperature of the Current Warm Period, which occurs at the end of their record in the AD 1990s in their MAT analysis,

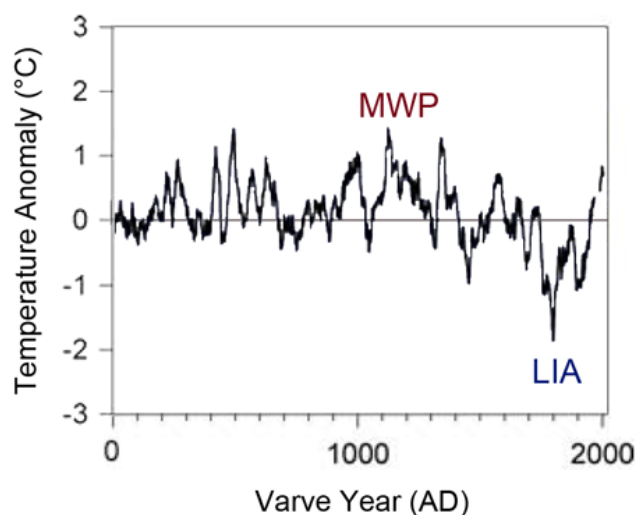


Figure 4.2.4.3.2.1.2. A proxy temperature reconstruction obtained from sediment cores extracted from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. Adapted from Cook, T.L., Bradley, R.S., Stoner, J.S., and Francus, P. 2009. Five thousand years of sediment transfer in a high arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. *Journal of Paleolimnology* **41**: 77–94.

and approximately 1.0°C warmer than the peak temperature of the CWP, which also occurs at the end of their record in their WAPLS analysis.

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4.2.4.3.2.2 Greenland

For many millennia, the Arctic climate, like that of Earth as a whole, 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. This subsection highlights studies that address the temperature history of Greenland.

Benthic foraminifera and lithofacies analyses were conducted by Jennings and Weiner (1996) on two marine sediment cores from Nansen Fjord, eastern Greenland (~68.25°N, 29.6°W) in an effort to infer changes in sea-ice conditions and water masses in the region since AD 730. The analyses revealed the presence of a Medieval Warm Period between about AD 730 and 1110, as depicted in Figure 4.2.4.3.2.2.1. The authors describe the climate during this time as “the warmest and most stable in the last millennium including the present day,” in which sea ice in the fjord was “never or rarely” present in the summer.

Dahl-Jensen *et al.* (1998) used temperature

measurements from two Greenland Ice Sheet boreholes to reconstruct the temperature history of this part of Earth over the past 50,000 years. Their data indicated that after the termination of the glacial period, temperatures steadily rose to a maximum of 2.5°C warmer than at present during the Holocene Climatic Optimum (4,000 to 7,000 years ago). The Medieval Warm Period (MWP) and Little Ice Age (LIA) also were observed in the record, with temperatures 1°C warmer and 0.5–0.7°C cooler than at the time of their writing, respectively. After the Little Ice Age, they report, temperatures once again rose, but they “decreased during the last decades,” indicating the MWP in this part of the Arctic was significantly warmer than it was just before the turn of the century.

Wagner and Melles (2001) extracted a 3.5-m-long sediment core from a lake (Raffels So) on an island (Raffles O) located just off Liverpool Land on the east coast of Greenland, which they analyzed for several properties related to the past presence of seabirds there, obtaining a 10,000-year record that tells much about the region's climate history. Key to the study were biogeochemical data, which, in the words of the two researchers, reflect “variations in seabird breeding colonies in the catchment which influence nutrient and cadmium supply to the lake.” These data revealed sharp increases in the values of the parameters they represented between about 1,100 and 700 years before present (BP), indicative of the summer presence of significant numbers of seabirds during that “medieval warm period,” as Wagner and Melles describe it, which was preceded by a several-hundred-year period (the Dark Ages Cold Period) with little or no bird presence. After the Medieval

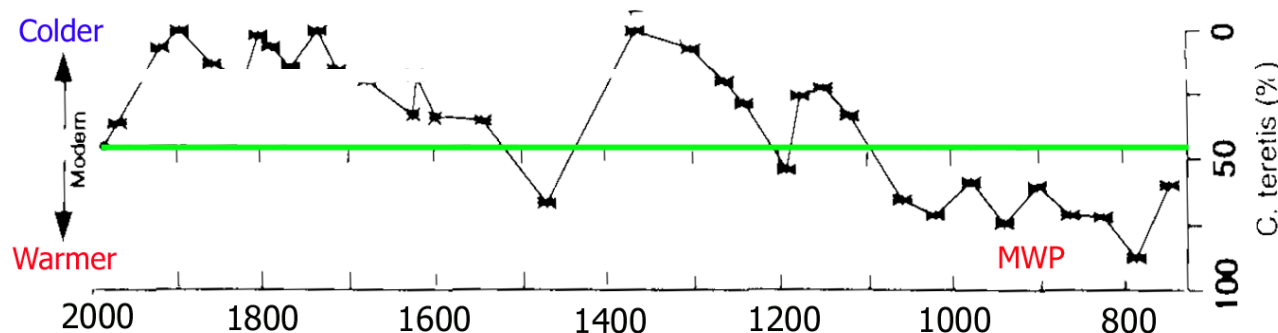


Figure 4.2.4.3.2.2.1. Percentage of *Cassidulina teretis*, an indicator of Atlantic Intermediate Water, in Nansen Fjord, Eastern Greenland. The horizontal green line indicates the modern percentage of *C. teretis*. Derivations below (above) this line indicate warmer (cooler) conditions. Adapted from Jennings, A.E. and Weiner, N.J. 1996. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. *The Holocene* **6**: 179–191.

Warm Period, their data suggest another absence of birds during what they call “a subsequent Little Ice Age,” which they say was “the coldest period since the early Holocene in East Greenland.”

The Raffles So data also show signs of a resettlement of seabirds during the last century, as indicated by an increase of organic matter in the lake sediment and confirmed by bird counts. Values of the most recent measurements of seabird numbers were not as great as those inferred for the earlier Medieval Warm Period, suggesting higher temperatures prevailed during much of the period from 1,100 to 700 years BP than those observed over the most recent hundred years.

Kaplan *et al.* (2002) derived a climate history of the Holocene by analyzing the physical-chemical properties of sediments obtained from a small lake in the southern sector of Greenland. The interval from 6,000 to 3,000 years BP was marked by warmth and stability, but the climate cooled thereafter until its culmination in the Little Ice Age. From 1300–900 years BP, there was a partial amelioration during the Medieval Warm Period, which was associated with an approximate 1.5°C rise in temperature.

Working on a floating platform in the middle of a small lake (Hjort So) on an 80-km-long by 10.5-km-wide island (Store Koldewey) just off the coast of Northeast Greenland, Wagner *et al.* (2008) recovered two sediment cores of 70 and 252 cm length, which they analyzed for grain-size distribution, macro-fossils, pollen, diatoms, total carbon, total organic carbon, and several other parameters. The sequences for those parameters were dated by accelerator mass spectrometry, with radiocarbon ages translated into calendar years before present. This revealed an “increase of the productivity-indicating proxies around 1,500–1,000 cal year BP, corresponding with the medieval warming,” and “after the medieval warming, renewed cooling is reflected in decreasing amounts of total organic carbon, total diatom abundance, and other organisms, and a higher abundance of oligotrophic to meso-oligotrophic diatom taxa.” They continue, “this period, the Little Ice Age, was the culmination of cool conditions during the Holocene and is documented in many other records from East and Northeast Greenland, before the onset of the recent warming [that] started ca. 150 years ago.”

In addition to finding evidence for the Medieval Warm Period, the six researchers’ statement that the Little Ice Age was the culmination, or most extreme subset, of cool conditions during the Holocene,

suggests it would not be at all unusual for such a descent into extreme coolness to be followed by some extreme warming, which further suggests there is nothing unusual about the degree of subsequent warming experienced over the twentieth century.

Norgaard-Pedersen and Mikkelsen (2009) analyzed materials obtained from a sediment core retrieved in August 2006 from the deepest basin of Narsaq Sound in southern Greenland, inferring various “glacio-marine environmental and climatic changes” that had occurred over the prior 8,000 years. This work revealed the existence of two periods (2.3–1.5 ka and 1.2–0.8 ka) that appeared to coincide roughly with the Roman and Medieval Warm Periods. They identified the colder period that followed the Medieval Warm Period as the Little Ice Age and the colder period that preceded it as the Dark Ages Cold Period. Citing the work of Dahl-Jensen *et al.* (1998), Andresen *et al.* (2004), Jensen *et al.* (2004), and Lassen *et al.* (2004), the two Danish scientists say the cold and warm periods identified in those studies “appear to be more or less synchronous to the inferred cold and warm periods observed in the Narsaq Sound record,” providing additional evidence for the reality of the naturally occurring phenomenon that governs this millennial-scale oscillation of climate.

Vinther *et al.* (2010) analyzed 20 ice core records from 14 sites, all of which stretched back at least 200 years, as well as near-surface air temperature data from 13 locations along the southern and western coasts of Greenland that covered approximately the same time interval (1784–2005), plus a similar temperature dataset from northwest Iceland, said by the authors to be employed “in order to have some data indicative of climate east of the Greenland ice sheet.” This work demonstrated winter $\delta^{18}\text{O}$ was “the best proxy for Greenland temperatures.” Based on that determination and working with three longer ice core $\delta^{18}\text{O}$ records (DYE-3, Crete and GRIP), they developed a temperature history that extended more than 1,400 years back in time.

This history revealed “temperatures during the warmest intervals of the Medieval Warm Period”—which they define as occurring some 900 to 1300 years ago—“were as warm as or slightly warmer than present day Greenland temperatures.” Vinther *et al.* also acknowledge the independent “GRIP borehole temperature inversion suggests central Greenland temperatures are still somewhat below the high temperatures that existed during the Medieval Warm Period.”

Kobashi *et al.* (2010) state, “in Greenland,

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oxygen isotopes of ice (Stuiver *et al.*, 1995) have been extensively used as a temperature proxy, but the data are noisy and do not clearly show multi-centennial trends for the last 1,000 years in contrast to borehole temperature records that show a clear ‘Little Ice Age’ and ‘Medieval Warm Period’ (Dahl-Jensen *et al.*, 1998).” They further note nitrogen (N) and argon (Ar) isotopic ratios— $^{15}\text{N}/^{14}\text{N}$ and $^{40}\text{Ar}/^{36}\text{Ar}$, respectively—can be used to construct a temperature record that “is not seasonally biased, and does not require any calibration to instrumental records, and resolves decadal to centennial temperature fluctuations.

They use this new approach to construct a history of the last thousand years of central Greenland surface air temperature, based on values of the isotopic ratios of nitrogen and argon previously derived by Kobashi *et al.* (2008) from air bubbles trapped in the GISP2 ice core that had been extracted from central Greenland, obtaining the result depicted in Figure 4.2.4.3.2.2.2.

This figure depicts the central Greenland surface temperature reconstruction produced by the six scientists. The peak temperature of the latter part of the Medieval Warm Period—which began some time prior to the start of their record, as demonstrated by the work of Dansgaard *et al.* (1975), Jennings and Weiner (1996), Johnsen *et al.* (2001), and Vinther *et al.* (2010)—appears to have been approximately 0.33°C greater than the peak temperature of the Current Warm Period and about 1.67°C greater than the temperature of the last decades of the twentieth century.

In a study based on the identification and quantification of various foraminiferal species found in a sediment core extracted from the bottom of a deep-water trough (Egedesminde Dyb) in the southwestern Disko Bugt of West Greenland at coordinates of $\sim 68^\circ 38'\text{N}$, $53^\circ 49'\text{W}$, Perner *et al.* (2011) derived a 3,600-year proxy-temperature history of the West Greenland Current at that location. This history revealed “a marked long-term cooling trend over the last 3.6 ka BP,” but superimposed on this longer-term cooling trend was evidence of millennial to centennial scale variability, where one of the warm intervals is said by them to constitute “the time period of the ‘Medieval Climate Anomaly,’” which they identify as occurring over the period AD 1000–1500. Their proxy-temperature graph indicates the entire period was significantly warmer than the Current Warm Period has been to date.

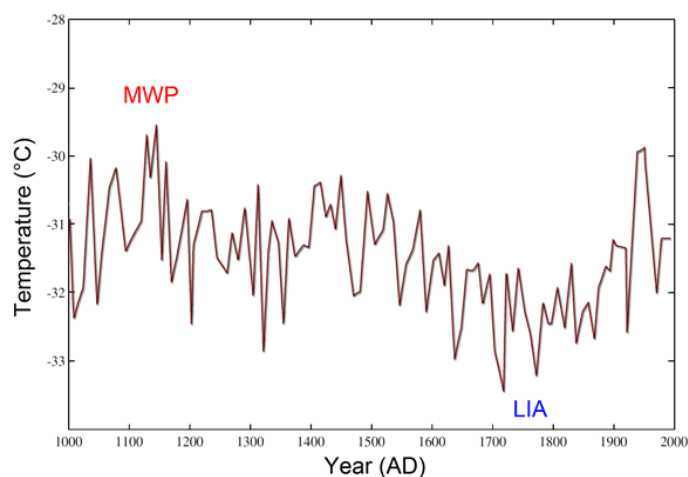


Figure 4.2.4.3.2.2.2. Central Greenland surface temperature reconstruction for the last millennium. Adapted from Kobashi, T., Severinghaus, J.P., Barnola, J.-M., Kawamura, K., Carter, T., and Nakaegawa, T. 2010. Persistent multi-decadal Greenland temperature fluctuation through the last millennium. *Climatic Change* **100**: 733–756.

Perner *et al.* (2013) identified and quantified the different types of benthic foraminiferal species found in two sediment cores beneath the path of the West Greenland Current (WGC) southwest of Disko Bugt ($68^\circ 28.311'\text{N}$, $54^\circ 00.119'\text{W}$) on the West Greenland margin, determining the relative thermal history of the WGC over the past 7,300 years. This record revealed “(1) cooling at ~ 2.5 ka BP, linked to the 2.7 ka BP ‘cooling event’, (2) a warm phase centered at 1.8 ka BP, associated with the ‘Roman Warm Period’, (3) slight warming between 1.4 and 0.9 ka BP, linked to the ‘Medieval Climate Anomaly’ [MCA], (4) severe cooling of the WGC after 0.9 ka BP, culminating at 0.3 ka BP during the ‘Little Ice Age.’” As to the degree of warmth of the MCA, the authors state, “our data show that oceanographic conditions (WGC) are relatively cool and remained cooler during the last 100 years than during the MCA,” indicating the warmth of the Current Warm Period has not reached that experienced during the MCA.

Axford *et al.* (2013) examined sedimentary records from five lakes (North, Fishtote, Loon, Iceboom, and Pluto) near Jakobshavn Isbrae in central West Greenland to investigate the timing and magnitude of major Holocene climate changes, with their primary objective being “to constrain the timing and magnitude of maximum warmth during the early to middle Holocene positive anomaly in summer insolation.” They did this by analyzing various

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properties of sediment cores extracted from the lakes in the summers of 2008 and 2009.

They write, “Based upon chironomid assemblages at North Lake, and supported by records of organic sedimentation in all five study lakes, we infer warmer-than-present temperatures by at least 7.1 ka [thousands of years before present] and Holocene maximum warmth between 6 and 4 ka,” when they indicate “the local ice sheet margin was at its most retracted Holocene position” and “summer temperatures were 2–3°C warmer than present during that time of minimum ice sheet extent.” A graphical representation of this temperature history is presented

in Figure 4.2.4.3.2.2.3, with the concomitant history of Earth’s atmospheric CO₂ concentration.

As illustrated in the figure, there is no relationship between the Holocene temperature history derived by Axford *et al.* and the air’s CO₂ content. Over the first 1,800 years of the record, when the atmosphere’s CO₂ concentration rose by just 10 ppm, Holocene temperatures rose, in the mean, by about 2.3°C. Then, over the following 2,400 years, when the air’s CO₂ content rose by about 20 ppm, mean summer air temperatures dropped by approximately 2.6°C. And over the next 1,900 years, when the air’s CO₂ content rose by 10 to 15 ppm,

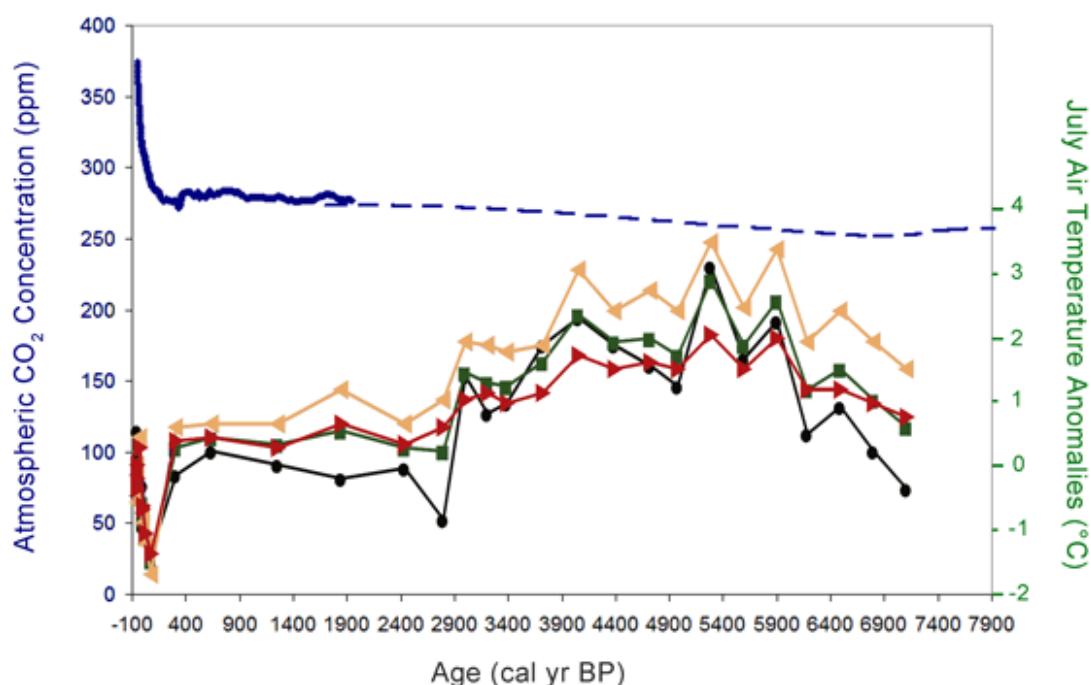


Figure 4.2.4.3.2.2.3. Reconstructed July air temperature anomalies in the vicinity of North Lake, inferred from chironomid data using three different calibration formulas: (1) Weighted-averaging, orange line with triangle data points, (2) Weighted-averaging with tolerance downweighting, red line with triangle data points, (3) Weighted-averaging partial-least-squares, black line with circle data points), plus the mean of the three sets of results (green line, square data points), as adapted from Axford, Y., Losee, S., Briner, J.P., Francis, D.R., Langdon, P.G., and Walker, I.R. 2013. Holocene temperature history at the western Greenland Ice Sheet margin reconstructed from lake sediments. *Quaternary Science Reviews* 59: 87–100. Also shown is the concomitant history of Earth’s atmospheric CO₂ concentration, as obtained from atmospheric measurements carried out at Mauna Loa, Hawaii (Boden, T.A., Kaiser, D.P., Sepanski, R.J., and Stoss, F.W. (Eds.) 1994. *Trends ‘93: A Compendium of Data on Global Change*. ORNL/CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee), together with ice core data obtained at Law Dome (Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.-M., and Morgan, V.I. 1998. Historical CO₂ records from the Law Dome DE08, DE08-2, and DSS ice cores. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.) and Vostock, Antarctica (Keeling, C.D. and Whorf, T.P. 1998. Atmospheric CO₂ concentrations—Mauna Loa Observatory, Hawaii, 1958–1997 (revised August 1998). NDP-001. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee).

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mean air temperature did not change. But over the final 300 or so years, when the atmospheric CO₂ concentration rose by 125 ppm, summer air temperatures first declined by about 1.9°C and then rose by about 1.9°C, for essentially no net change. The CO₂ concentration of Earth's atmosphere shows no consistent impact on July air temperatures in the vicinity of North Lake, Greenland, over the past seven millennia.

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4.2.4.3.2.3 Russia/Asian Arctic

Naurzbaev and Vaganov (2000) developed a 2,200-year temperature history using tree-ring data obtained from 118 trees near the upper-timberline in Siberia for the period 212 BC to AD 1996, as well as a similar history covering the period of the Holocene Climatic Optimum (3300 to 2600 BC). They compared their results with those obtained from an analysis of isotopic oxygen data extracted from a Greenland ice core. Fluctuations in average annual temperature derived from the Siberian record agreed well with air temperature variations reconstructed from the Greenland data, suggesting “the tree ring chronology of [the Siberian] region can be used to analyze both regional peculiarities and global temperature variations in the Northern Hemisphere.”

Naurzbaev and Vaganov report several warm and cool periods prevailed for several multi-century periods throughout the last two millennia: a cool period in the first two centuries AD, a warm period from AD 200 to 600, cooling again from 600 to 800 AD, followed by the Medieval Warm Period from about AD 850 to 1150, the cooling of the Little Ice Age from AD 1200 through 1800, followed by the recovery warming of the twentieth century. The latter temperature rise was “not extraordinary,” they write, and “the warming at the border of the first and second millennia [AD 1000] was longer in time and similar in amplitude.” In addition, their reconstructed temperatures for the Holocene Climatic Optimum reveal there was an even warmer period about 5,000 years ago, when temperatures averaged 3.3°C more than over the past two millennia.

Vaganov *et al.* (2000) also used tree-ring width as a temperature proxy, reporting temperature variations for the Asian subarctic region over the past 600 years. Their graph of these data reveals temperatures in this region exhibited a small positive trend from the beginning of the record until about AD 1750. Thereafter, a severe cooling trend ensued, followed by a 130-year warming trend from about 1820

through 1950, after which temperatures fell once again. Vaganov *et al.* determined the amplitude of twentieth century warming “does not go beyond the limits of reconstructed natural temperature fluctuations in the Holocene subarctic zone.” They further report finding a significant correlation with solar radiation and volcanic activity over the entire 600-year period ($r = 0.32$ for solar radiation, $r = -0.41$ for volcanic activity), which improved over the shorter interval (1800–1990) of the industrial period ($r = 0.68$ for solar radiation, $r = -0.59$ for volcanic activity).

Naurzbaev *et al.* (2002) developed a 2,427-year proxy temperature history for the part of the Taimyr Peninsula, northern Russia, lying between 70°30' and 72°28' North latitude, based on a study of ring-widths of living and preserved larch trees, noting it has been shown “the main driver of tree-ring variability at the polar timber-line [where they worked] is temperature (Vaganov *et al.*, 1996; Briffa *et al.*, 1998; Schweingruber and Briffa, 1996).” They found “the warmest periods over the last two millennia in this region were clearly in the third [Roman Warm Period], tenth to twelfth [Medieval Warm Period] and during the twentieth [Current Warm Period] centuries.” With respect to the second of these three periods, they emphasize “the warmth of the two centuries AD 1058–1157 and 950–1049 attests to the reality of relative mediaeval warmth in this region.” Their data also reveal the Roman and Medieval Warm Periods were warmer than the Current Warm Period has been to date; the beginning of the end of the Little Ice Age was somewhere in the vicinity of 1830; and the Current Warm Period peaked somewhere around 1940.

All of these observations are at odds with what is portrayed in the Northern Hemispheric hockey stick temperature history of Mann *et al.* (1998, 1999) and its thousand-year global extension developed by Mann and Jones (2003), in which the Current Warm Period is depicted as the warmest such era of the past two millennia, recovery from the Little Ice Age does not begin until after 1910, and the Current Warm Period experiences its highest temperatures in the latter part of the twentieth century’s final decade.

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4.2.4.3.2.4 Scandinavia and Iceland

Jiang *et al.* (2002) analyzed diatom assemblages from a high-resolution core extracted from the seabed of the north Icelandic shelf, which led to their reconstruction of a 4,600-year history of summer sea surface temperature at that location. Starting from a maximum value of about 8.1°C at 4,400 years BP, the climate was found to have cooled fitfully for about 1,700 years and then more consistently over the final 2,700 years of the record. The most dramatic departure from this long-term decline was centered on about 850 years BP, during the Medieval Warm Period, when the temperature rose by more than 1°C above the line describing the long-term downward

trend to effect an almost complete recovery from the colder temperatures of the Dark Ages Cold Period, after which temperatures continued their descent into the Little Ice Age, ending with a final most recent value of approximately 6.3°C. Their data clearly show the Medieval Warm Period in this part of the Arctic was significantly warmer than it is there now.

Grudd *et al.* (2002) assembled tree-ring widths from 880 living, dead, and subfossil northern Swedish pines into a continuous and precisely dated chronology covering the period 5407 BC to AD 1997. The strong association between these data and summer (June–August) mean temperatures of the last 129 years of the period enabled them to produce a 7,400-year history of summer mean temperature for northern Swedish Lapland.

The most dependable portion of this record, based on the number of trees that were sampled, consisted of the last two millennia, which Grudd *et al.* say “display features of century-timescale climatic variation known from other proxy and historical sources, including a warm ‘Roman’ period in the first centuries AD and a generally cold ‘Dark Ages’ climate from about AD 500 to about AD 900.” They also note “the warm period around AD 1000 may correspond to a so-called ‘Mediaeval Warm Period,’ known from a variety of historical sources and other proxy records.” They state, “the climatic deterioration in the twelfth century can be regarded as the starting point of a prolonged cold period that continued to the first decade of the twentieth century,” and this “Little Ice Age,” in their words, is also “known from instrumental, historical and proxy records.” Going back even further in time, the tree-ring record displays several more of these relatively warmer and colder periods. They report “the relatively warm conditions of the late twentieth century do not exceed those reconstructed for several earlier time intervals.”

Seppa and Birks (2002) used a recently developed pollen-climate reconstruction model and a new pollen stratigraphy from Toskaljavri, a tree-line lake in the continental sector of northern Fennoscandia located just above 69°N latitude, to derive quantitative estimates of annual precipitation and July mean temperature. Their reconstructions “agree with the traditional concept of a ‘Medieval Warm Period’ (MWP) and ‘Little Ice Age’ in the North Atlantic region (Dansgaard *et al.*, 1975) and in northern Fennoscandia (Korhola *et al.*, 2000).” In addition, they report there was “a clear correlation between [their] MWP reconstruction and several records from Greenland ice cores,” and “comparisons of a

smoothed July temperature record from Toskaljavri with measured borehole temperatures of the GRIP and Dye 3 ice cores (Dahl-Jensen *et al.*, 1998) and the $\delta^{18}\text{O}$ record from the Crete ice core (Dansgaard *et al.*, 1975) show the strong similarity in timing of the MWP between the records.” They also note, “July temperature values during the Medieval Warm Period (ca. 1400–1000 cal yr B.P.) were ca. 0.8°C higher than at present,” where present means the last six decades of the twentieth century.

Isaksson *et al.* (2003) retrieved two ice cores (one from Lomonosovfonna and one from Austfonna) far above the Arctic Circle in Svalbard, Norway, after which the 12 scientists from Norway, Finland, Sweden, Canada, Japan, Estonia, and the Netherlands used $\delta^{18}\text{O}$ data to reconstruct a 600-year temperature history of the region. As would be expected in light of Earth’s transition from the Little Ice Age to the Current Warm Period, the scientists report “the $\delta^{18}\text{O}$ data from both Lomonosovfonna and Austfonna ice cores suggest that the 20th century was the warmest during at least the past 600 years.” However, the warmest decade of the twentieth century was centered on approximately 1930, and the instrumental temperature record at Longyearbyen also shows the decade of the 1930s to have been the warmest. The authors note, “as on Svalbard, the 1930s were the warmest decade in the Trondheim record.” There was no net warming over the last seven decades of the twentieth century in the parts of Norway cited in this study.

Knudsen *et al.* (2004) documented climate changes over the past 1,200 years via high-resolution multi-proxy studies of benthic and planktonic foraminiferal assemblages, stable isotopes, and ice-rafted debris found in three sediment cores retrieved from the North Icelandic shelf. They learned “the time period between 1200 and around 7–800 cal. (years) BP, including the Medieval Warm Period, was characterized by relatively high bottom and surface water temperatures,” after which “a general temperature decrease in the area marks the transition to ... the Little Ice Age.” They also found “minimum sea-surface temperatures were reached at around 350 cal. BP, when very cold conditions were indicated by several proxies.” Thereafter, they report, “a modern warming of surface waters ... is not registered in the proxy data” and “there is no clear indication of warming of water masses in the area during the last decades,” even in sea surface temperatures measured over the period 1948–2002.

Bradwell *et al.* (2006) examined the link between

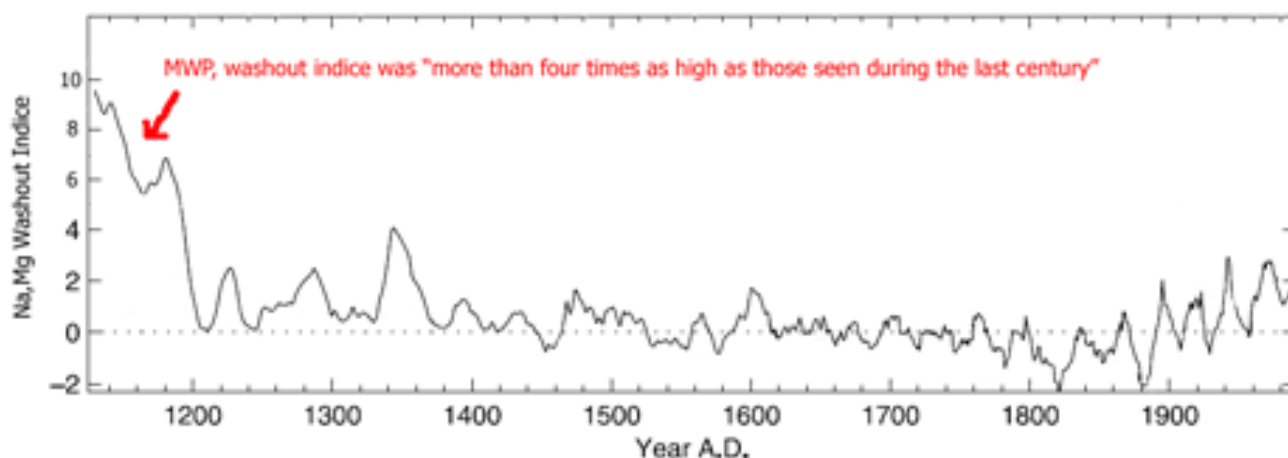
late Holocene fluctuations of Lambatungnajokull (an outlet glacier of the Vatnajokull ice cap of southeast Iceland) and variations in climate, using geomorphological evidence to reconstruct patterns of past glacier fluctuations and lichenometry and tephrostratigraphy to date glacial landforms created by the glacier over the past four centuries. This work revealed “a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat” and “between 1930 and 1950 this relationship is striking.” They also report, “ice-front recession was greatest during the 1930s and 1940s, when retreat averaged 20 m per year.” Thereafter, the retreat “slowed in the 1960s” and “there has been little overall retreat since the 1980s.”

The researchers also report, “the 20th-century record of reconstructed glacier-front fluctuations at Lambatungnajokull compares well with those of other similar-sized, non-surging, outlets of southern Vatnajokull,” including Skaftafellsjokull, Fjallsjokull, Skalafellsjokull, and Flaajokull. They find “the pattern of glacier fluctuations of Lambatungnajokull over the past 200 years reflects the climatic changes that have occurred in southeast Iceland and the wider region.”

Bradwell *et al.*’s findings indicate twentieth century summer air temperature in southeast Iceland and the wider region peaked in the 1930s and 1940s, and this warming was followed by a cooling that persisted through the end of the century. This history is about as different as can be imagined from the claim the warming of the globe over the last two decades of the twentieth century was unprecedented over the past two millennia, and this is especially significant for a high-northern-latitude region, where the IPCC claims CO₂-induced global warming should be earliest and most strongly expressed.

Grinsted *et al.* (2006) developed “a model of chemical fractionation in ice based on differing elution rates for pairs of ions ... as a proxy for summer melt (1130–1990),” based on data obtained from a 121-meter-long ice core they extracted from the highest ice field in Svalbard (Lomonosovfonna: 78°51’53”N, 17°25’30”E), which was “validated against twentieth-century instrumental records and longer historical climate proxies.” This history shows, as illustrated in Figure 4.2.4.3.2.4.1, “in the oldest part of the core (1130–1200), the washout indices [were] more than 4 times as high as those seen during the last century, indicating a high degree of runoff.” In addition, regular snow pit studies conducted near

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15-year moving average of a washout indice derived from Na and Mg data from a Lomonosovfonna ice core, which data are a proxy for summer ice melt. Adapted from Grinsted et al. 2006

Figure 4.2.4.3.2.4.1. Fifteen-year moving average of a washout indice derived from Na and Mg data from a Lomonosovfonna ice core on Svalbard, which data are a proxy for summer ice melt. Adapted from Grinsted, A., Moore, J.C., Pohjola, V., Martma, T., and Isaksson, E. 2006. Svalbard summer melting, continentality, and sea ice extent from the Lomonosovfonna ice core. *Journal of Geophysical Research* **111**: 10.1029/2005JD006494..

the ice core site since 1997 (Virkkunen, 2004) found “the very warm 2001 summer resulted in similar loss of ions and washout ratios as the earliest part of the core.” Grinsted *et al.* state, “this suggests that the Medieval Warm Period in Svalbard summer conditions [was] as warm (or warmer) as present-day, consistent with the Northern Hemisphere temperature reconstruction of Moberg *et al.* (2005).” In addition, they conclude “the degree of summer melt was significantly larger during the period 1130–1300 than in the 1990s,” which suggests a large portion of the Medieval Warm Period was significantly warmer than the peak warmth of the Current Warm Period.

Noting the varve thicknesses of annually laminated sediments laid down by Hvitarvatn, a proglacial lake in the central highlands of Iceland, is controlled by the rate of glacial erosion and efficiency of subglacial discharge from the adjacent Langjökull ice cap, Larsen *et al.* (2011) employed a suite of environmental proxies contained in those sediments to reconstruct the region’s climate variability and glacial activity over the past 3,000 years. These proxies included varve thickness, varve thickness variance, ice-rafted debris, total organic carbon (mass flux and bulk concentration), and the C:N ratio of sedimentary organic matter. The scientists found “all proxy data reflect a shift toward increased glacial erosion and landscape destabilization from ca 550 AD to ca 900 AD and from ca 1250 AD to ca 1950 AD,

separated by an interval of relatively mild conditions.” They note, “the timing of these intervals coincides with the well-documented periods of climate change commonly known as the Dark Ages Cold Period, the Medieval Warm Period, and the Little Ice Age.”

In the case of the Medieval Warm Period, they note, “varve thickness decreases after 950 AD and remains consistently low through Medieval time with slightly thinner annual laminations than for any other multi-centennial period in the past 3000 years,” which suggests the MWP was the warmest period of the past three millennia. They state, “the LIA was the most severe multi-centennial cold interval of the late Holocene” and “likely since regional deglaciation 10,000 years ago.”

The 12 researchers of Esper *et al.* (2012), from Finland, Germany, Scotland, and Switzerland, write, “solar insolation changes, resulting from long-term oscillations of orbital configurations (Milankovitch, 1941), are an important driver of Holocene climate,” referencing the studies of Mayewski *et al.* (2004) and Wanner *et al.* (2008). They note this forcing has been “substantial over the past 2000 years, up to four times as large as the 1.6 Wm^{-2} net anthropogenic forcing since 1750,” as suggested by the work of Berger and Loutre (1991). On the basis of “numerous high-latitude proxy records,” they note “slow orbital changes have recently been shown to gradually force

boreal summer temperature cooling over the common era,” citing Kaufman *et al.* (2009).

Esper *et al.* (2012) developed “a 2000-year summer temperature reconstruction based on 587 high-precision maximum latewood density (MXD) series from northern Scandinavia,” accomplished “over three years using living and subfossil pine (*Pinus sylvestris*) trees from 14 lakes and 3 lakeshore sites above 65°N, making it not only longer but also much better replicated than any existing MXD time series.” After calibrating the pine MXD series against regional June–July–August mean temperature over the period 1876–2006, they obtained their final summer temperature history for the period stretching from 138 BC to AD 2006, as depicted in Figure 4.2.4.3.2.4.2.

Esper *et al.* calculate a long-term cooling trend of $-0.31 \pm 0.03^\circ\text{C}$ per thousand years, which they say is “missing in published tree-ring proxy records” but is “in line with coupled general circulation models (Zorita *et al.*, 2005; Fischer and Jungclaus, 2011).” These computational results portray, as they describe it, substantial summer cooling over the past two millennia in northern boreal and Arctic latitudes.

“These findings,” the researchers continue, “together with the missing orbital signature in published dendrochronological records, suggest that large-scale near-surface air temperature reconstructions (Mann *et al.*, 1999; Esper *et al.*, 2002; Frank *et al.*, 2007; Hegerl *et al.*, 2007; Mann *et al.*, 2008) relying on tree-ring data may underestimate pre-instrumental temperatures including warmth during Medieval and Roman times,” although they suggest the impacts of the omitted long-term trend in basic tree-ring data may “diminish towards lower Northern Hemisphere latitudes, as the forcing and radiative feedbacks decrease towards equatorial regions.”

Why was much of the CO₂-starved world of Medieval and Roman times decidedly warmer (by about 0.3 and 0.5°C, respectively) than during the peak warmth of the twentieth century? If the greenhouse effect of atmospheric CO₂ has not been grossly overestimated, then it must currently be significantly tempered by some unappreciated negative-feedback phenomenon such that the basic greenhouse effect of Earth’s rising atmospheric CO₂ concentration cannot fully compensate for the

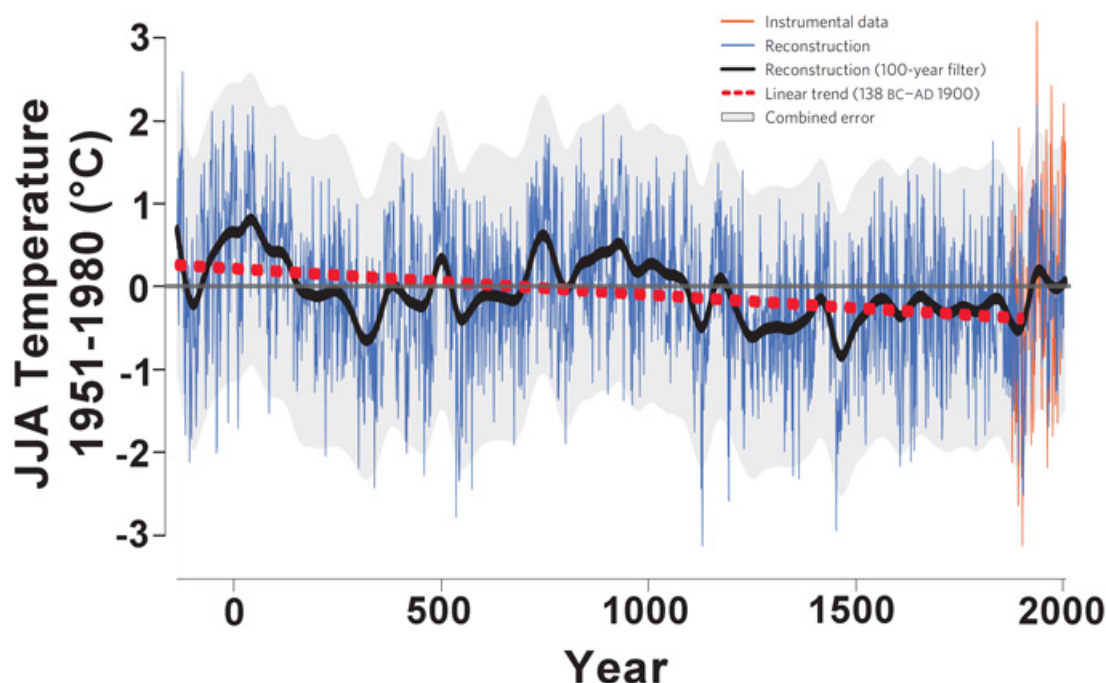


Figure 4.2.4.3.2.4.2. The summer (June–July–August) temperature reconstruction of Esper *et al.* (2012), adapted from Esper, J., Frank, D.C., Timonen, M., Zorita, E., Wilson, R.J.S., Luterbacher, J., Holzkamper S., Fischer, N., Wagner, S., Nievergelt, D., Verstege, A., and Buntgen, U. 2012. Orbital forcing of tree-ring data. *Nature Climate Change*: DOI 10.1038/NCLIMATE1589.

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decrease in solar insolation experienced over the past two millennia as a result of the “long-term oscillations of orbital configurations” cited by Esper *et al.* (2012).

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4.2.4.3.2.5 The Rest of the Arctic

Overpeck *et al.* (1997) combined paleoclimatic records obtained from lake and marine sediments, trees, and glaciers to develop a 400-year history of circum-Arctic surface air temperature. From this record they determined the most dramatic warming of the last four centuries of the past millennium (1.5°C) occurred between 1840 and 1955, over which period the air's CO₂ concentration rose by 28 ppm, from approximately 285 ppm to 313 ppm. From 1955 to the end of the record (about 1990), the mean circum-Arctic air temperature declined by 0.4°C, while the air's CO₂ concentration rose by 41 ppm, from 313 ppm to 354 ppm.

Thus, over the first 115 years of Overpeck *et al.*'s record, as the air's CO₂ concentration rose by an average of 0.24 ppm/year, air temperature rose by an average of 0.013°C/year. Over the final 35 years of the record, when the air's CO₂ content rose at a mean rate of 1.17 ppm/year (nearly five times as fast), the rate-of-rise of surface air temperature *decelerated*, to a mean value (0.011°C/year), just the opposite of what one would have expected on the basis of greenhouse gas-induced warming theory.

Benner *et al.* (2004) noted, “thawing of the permafrost which underlies a substantial fraction of the Arctic could accelerate carbon losses from soils (Goulden *et al.*, 1998).” In addition, “freshwater

discharge to the Arctic Ocean is expected to increase with increasing temperatures (Peterson *et al.*, 2002), potentially resulting in greater riverine export of terrigenous organic carbon to the ocean.” And since the organic carbon in Arctic soils “is typically old, with average radiocarbon ages ranging from centuries to millennia (Schell, 1983; Schirrmeister *et al.*, 2002),” they set about to measure the age of dissolved organic carbon (DOC) in Arctic rivers to determine whether increasing amounts of older carbon were being transported to the ocean, which would indicate enhanced regional warming.

The researchers sampled two of the largest Eurasian rivers, the Yenisey and Ob', which drain vast areas of boreal forest and extensive peat bogs, accounting for about a third of all riverine DOC discharge to the Arctic Ocean, as well as two much smaller rivers on the north slope of Alaska, the Ikpikpuk and Kokolik, whose watersheds are dominated by Arctic tundra. They found modern radiocarbon ages for all samples taken from all rivers, which indicate, they write, Arctic riverine DOC “is derived primarily from recently fixed plant litter and near-surface soil horizons.” Because warming should have caused the average radiocarbon age of the DOC of Arctic rivers to increase, the absence of aging implied by their findings provides strong evidence for the absence of recent large-scale warming there.

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4.2.4.3.3 The Past One to Two Centuries

The IPCC contends current temperatures are both unnatural and unprecedented, as a result of global warming caused by anthropogenic CO₂ emissions, and they claim this “unnaturalness” is most strongly expressed in the world’s Arctic regions. Here we investigate that claim in the context of the past one to two centuries.

The studies reviewed here lead to the conclusion that, in spite of the model-based concerns about the Arctic being at a “tipping point” and beginning to experience unprecedented warming and irreversible ice loss, there is nothing unusual, unnatural, or unprecedented about current Arctic temperatures. Warming over the past three decades or so has been generally less impressive than a similar warming that occurred several decades earlier in the 1920s–1940s, and it becomes still less impressive when taking into consideration the atmosphere’s CO₂ concentration rose by only about 5 ppm during the earlier period of stronger warming but by fully 25 ppm during the later period of weaker warming.

4.2.4.3.3.1 Greenland

Comiso *et al.* (2001) utilized satellite imagery to analyze and quantify several attributes of the Odden ice tongue, a winter ice-cover phenomenon that occurs in the Greenland Sea with a length of about 1,300 km and an aerial coverage of as much as 330,000 square kilometers, including its average concentration, maximum area, and maximum extent over the period 1979–1998. In addition, they used surface air temperature data from Jan Mayen Island, located within the region of study, to infer the behavior of the phenomenon over the past 75 years.

The Odden ice tongue was found to vary in size, shape, and length of occurrence during the 20-year period, displaying a fair amount of interannual variability. Trend analyses revealed the ice tongue had exhibited no statistically significant change in any of the parameters studied over the short 20-year

period, but a proxy reconstruction for the past 75 years revealed the ice phenomenon to have been “a relatively smaller feature several decades ago,” due to the significantly warmer temperatures that prevailed at that time.

The Odden ice tongue’s persistence, virtually unchanged in the mean during the past 20 years, is in direct contrast with model predictions of rapid and increasing warmth in Earth’s polar regions as a result of CO₂-induced global warming. This observation, along with the evidence from Jan Mayen Island that temperatures there actually cooled at a rate of $0.15 \pm 0.03^{\circ}\text{C}$ per decade during the past 75 years, confirms there has been little or no warming in this part of the Arctic over the past seven decades.

Hanna and Cappelen (2003) determined the air temperature history of coastal southern Greenland from 1958–2001 based on data from eight Danish Meteorological Institute stations in coastal and near-coastal southern Greenland, as well as the concomitant sea surface temperature (SST) history of the Labrador Sea off southwest Greenland based on three previously published and subsequently extended SST datasets (Parker *et al.*, 1995; Rayner *et al.*, 1996; Kalnay *et al.*, 1996). The coastal temperature data showed a cooling of 1.29°C over the period of study, while two of the three SST databases also depicted cooling: by 0.44°C in one case and by 0.80°C in the other. The land-based air temperature and SST series followed similar patterns and were strongly correlated, but with no obvious lead/lag either way. In addition, the researchers determined the cooling was “significantly inversely correlated with an increased phase of the North Atlantic Oscillation (NAO) over the past few decades.” The two researchers state this “NAO-temperature link doesn’t explain what caused the observed cooling in coastal southern Greenland but it does lend it credibility.” In referring to what they call “this important regional exception to recent ‘global warming,’” Hanna and Cappelen note the “recent cooling may have significantly added to the mass balance of at least the southern half of the [Greenland] Ice Sheet.” Since this part of the ice sheet would likely be the first to experience melting in a warming world, it would appear whatever caused the cooling has not only protected the Greenland Ice Sheet against warming-induced disintegration but actually fortified it against that possibility.

Taurisano *et al.* (2004) studied the temperature history of the Nuuk fjord during the past century, and their analyses of all pertinent regional data led them to conclude “at all stations in the Nuuk fjord, both the

annual mean and the average temperature of the three summer months (June, July and August) exhibit a pattern in agreement with the trends observed at other stations in south and west Greenland (Humlum 1999; Hanna and Cappelen, 2003).” They report the temperature data “show that a warming trend occurred in the Nuuk fjord during the first 50 years of the 1900s, followed by a cooling over the second part of the century, when the average annual temperatures decreased by approximately 1.5°C.” Coincident with this cooling trend there was “a remarkable increase in the number of snowfall days (+59 days).” Moreover, they report “not only did the cooling affect the winter months, as suggested by Hannna and Cappelen (2002), but also the summer mean,” noting “the summer cooling is rather important information for glaciological studies, due to the ablation-temperature relations.”

Chylek *et al.* (2004) analyzed data from three coastal stations in southern and central Greenland that possessed almost uninterrupted temperature records between 1950 and 2000, discovering “summer temperatures, which are most relevant to Greenland ice sheet melting rates, do not show any persistent increase during the last fifty years.” Working with the two stations with the longest records (both over a century in length), they determined coastal Greenland’s peak temperatures occurred between 1930 and 1940, and the subsequent decline in temperature was so substantial and sustained that temperatures at the end of the millennium were “about 1°C below their 1940 values.” They also found “at the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of 2.2°C per decade since the beginning of the measurements in 1987.” Therefore, much of Greenland did not experience any net warming, but rather cooled significantly, over the most dramatic period of atmospheric CO₂ increase on record.

At the start of the twentieth century, however, Greenland was warming, as it emerged, along with the rest of the world, from the depths of the Little Ice Age. Between 1920 and 1930, when the atmosphere’s CO₂ concentration rose by a mere 3 to 4 ppm, there was a phenomenal warming at all five coastal locations for which contemporary temperature records are available. Chylek *et al.* report, “average annual temperature rose between 2 and 4°C [and by as much as 6°C in the winter] in less than ten years.” This warming, they note, “is also seen in the ¹⁸O/¹⁶O record of the Summit ice core (Steig *et al.*, 1994; Stuiver *et al.*, 1995; White *et al.*, 1997).”

In commenting on this dramatic temperature rise, which they call the great Greenland warming of the 1920s, Chylek *et al.* conclude, “since there was no significant increase in the atmospheric greenhouse gas concentration during that time, the Greenland warming of the 1920s demonstrates a large and rapid temperature increase can occur over Greenland, and perhaps in other regions of the Arctic, due to internal climate variability such as the NAM/NAO [Northern Annular Mode/North Atlantic Oscillation], without a significant anthropogenic influence.”

Laidre and Heide-Jorgensen (2005) published a somewhat unusual paper, in that it dealt with the danger of oceanic cooling. Using a combination of long-term satellite tracking data, climate data, and remotely sensed sea-ice concentrations to detect localized habitat trends of narwhals in Baffin Bay between Greenland and Canada, home to the largest narwhal population in the world, they studied the species’ vulnerability to recent and possible future climate trends. They report, “since 1970, the climate in West Greenland has cooled, reflected in both oceanographic and biological conditions (Hanna and Cappelen, 2003),” with the result that “Baffin Bay and Davis Strait display strong significant increasing trends in ice concentrations and extent, as high as 7.5% per decade between 1979 and 1996, with comparable increases detected back to 1953 (Parkinson *et al.*, 1999; Deser *et al.*, 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002; Stern and Heide-Jorgensen, 2003).”

The two researchers also report, “cetacean occurrence is generally negatively correlated with dense or complete ice cover due to the need to breathe at the surface,” and “lacking the ability to break holes in the ice,” narwhals are vulnerable to reductions in the amount of open water available to them, as has been demonstrated by ice entrapment events “where hundreds of narwhals died during rapid sea ice formation caused by sudden cold periods (Siegestad and Heide-Jorgensen, 1994; Heide-Jorgensen *et al.*, 2002).” Such events were becoming increasingly likely as temperatures continued to decline and sea-ice cover and variability increased, and the scientists found the latter two trends to be “highly significant at or above the 95% confidence level.” They conclude, “with the evidence of changes in sea ice conditions that could impact foraging, prey availability, and of utmost importance, access to the surface to breathe, it is unclear how narwhal sub-populations will fare in light of changes in the high Arctic.”

Chylek *et al.* (2006) studied the characteristics of

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two century-long temperature records from southern coastal Greenland—Godthab Nuuk on the west and Ammassalik on the east, both close to 64°N latitude—concentrating on the period 1915–2005. As they describe it, “although the whole decade of 1995–2005 was relatively warm, the temperatures at Godthab Nuuk and Ammassalik were not exceptionally high,” as “almost all decades between 1915 and 1965 were warmer than, or at least as warm as, the 1995 to 2005 decade, suggesting the current warm Greenland climate is not unprecedented and that similar temperatures were [the] norm in the first half of the 20th century.” They also 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.” They report the earlier warming rate was 50 percent greater than the most recent one.

In comparing the southern coastal Greenland temperature record with that of the entire globe for the same time period, Chylek *et al.* note, “while all the decadal averages of the post-1955 global temperature are higher than the pre-1955 average, almost all post-1995 temperature averages at Greenland stations are lower than the pre-1955 temperature average.” The three researchers also note, “the summer temperature at the Summit of the Greenland ice sheet shows a decreasing tendency since the beginning of the measurements in 1986 (Chylek *et al.*, 2004).”

In light of these observations, Chylek *et al.* say, “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 note “the Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary 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.” In addition, “a general increase in solar activity (Scafetta and West, 2006) since [the] 1990s can be a contributing factor, as well as the sea surface temperature changes of [the] tropical ocean (Hoerling *et al.*, 2001).”

Chylek *et al.* note, “glacier acceleration observed during the 1996–2005 period (Rignot and Kanagaratnam, 2006) has probably occurred previously,” and “there should have been the same or more extensive acceleration during the 1920–1930

warming as well as during the Medieval Warm Period in Greenland (Dahl-Jensen *et al.*, 1998; DeMenocal *et al.*, 2000) when Greenland temperatures were generally higher than today.” As Chylek *et al.* put it, “we find no direct evidence to support the claims that the Greenland ice sheet is melting due to increased temperature caused by increased atmospheric concentration of carbon dioxide.”

Hansen *et al.* (2006) analyzed meteorological data from Arctic Station (69°15'N, 53°31'W) on Disko Island (West Greenland) for the period 1991–2004, after which their results were correlated “to the longest record available from Greenland at Ilulissat/Jakobshavn (since 1873).” Marked changes were noted over the study period, including “increasing mean annual air temperatures on the order of 0.4°C per year and 50% decrease in sea ice cover.” In addition, due to “a high correlation between mean monthly air temperatures at the two stations (1991–2004),” Hansen *et al.* placed the air temperature trend observed at Disko “in a 130 years perspective.” This led them to conclude the climate changes of the last decade were “dramatic,” but “similar changes in air temperatures [had] occurred previous[ly] within the last 130 years.” They report the changes they observed over the last decade “are on the same order as changes [that] occurred between 1920 and 1930.”

Drinkwater (2006) “provide[d] a review of the changes to the marine ecosystems of the northern North Atlantic during the 1920s and 1930s and ... discuss[ed] them in the light of contemporary ideas of regime shifts,” where he defined regime shift as “a persistent radical shift in typical levels of abundance or productivity of multiple important components of the marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent.” He first determined “in the 1920s and 1930s, there was a dramatic warming of the air and ocean temperatures in the northern North Atlantic and the high Arctic, with the largest changes occurring north of 60°N,” and this warming “led to reduced ice cover in the Arctic and subarctic regions and higher sea temperatures,” as well as northward shifts of multiple marine ecosystems. This change in climate occurred, he writes, “during the 1920s, and especially after 1925,” when “average air temperatures began to rise rapidly and continued to do so through the 1930s,” at which point “mean annual air temperatures increased by approximately 0.5–1°C and the cumulative sums of anomalies varied from 1.5 to 6°C between 1920 and 1940 with the higher values occurring in West

Greenland and Iceland.” Thereafter, “through the 1940s and 1950s air temperatures in the northernmost regions varied but generally remained relatively high,” declining in the late 1960s in the northwest Atlantic and slightly earlier in the northeast Atlantic. This cooling only recently has begun to be reversed in certain parts of the region.

In the realm of biology, the early twentieth century warming of North Atlantic waters “contributed to higher primary and secondary production,” in the words of Drinkwater, and “with the reduced extent of ice-covered waters, more open water allow[ed] for higher production than in the colder periods.” Cod “spread approximately 1200 km northward along West Greenland” and “migration of ‘warmer water’ species also changed with earlier arrivals and later departures.” In addition, Drinkwater notes, “new spawning sites were observed farther north for several species or stocks while for others the relative contribution from northern spawning sites increased.” Also, “some southern species of fish that were unknown in northern areas prior to the warming event became occasional, and in some cases, frequent visitors.” Drinkwater concludes, “the warming in the 1920s and 1930s is considered to constitute the most significant regime shift experienced in the North Atlantic in the 20th century.”

Vinther *et al.* (2006) combined early observational records from 13 locations along the southern and western coasts of Greenland to extend the overall temperature history of the region—which stretches from approximately 60 to 73°N latitude—back to AD 1784, adding temperatures for 74 complete winters and 52 complete summers to what previously was available to the public. The authors report, “two distinct cold periods, following the 1809 ‘unidentified’ volcanic eruption and the eruption of Tambora in 1815, [made] the 1810s the coldest decade on record.” They found “the warmest year in the extended Greenland temperature record [was] 1941, while the 1930s and 1940s [were] the warmest decades.” Their newly lengthened record revealed there has been no net warming of the region over the past 75 years.

Approximately half of the Vinther *et al.* study region was located above the Arctic Circle, where CO₂-induced global warming is suggested by climate models to be most evident and earliest expressed. One thus would have expected to see southwestern coastal Greenland’s air temperature responding vigorously to the 75 ppm increase in the atmosphere’s CO₂ concentration since 1930, even if the models were

only half-correct. But no net change in air temperature has occurred there in response to the 25 percent increase in the air’s CO₂ content experienced over that period.

Mernild *et al.* (2008) described “the climate and observed climatic variations and trends in the Mittivakkat Glacier catchment in Low Arctic East Greenland from 1993 to 2005 ... based on the period of detailed observations (1993–2005) and supported by synoptic meteorological data from the nearby town of Tasiilaq (Ammassalik) from 1898 to 2004.” The authors report, “the Mittivakkat Glacier net mass balance has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% per year.” During the past century of general mass loss, they found “periods of warming were observed from 1918 (the end of the Little Ice Age) to 1935 of 0.12°C per year and 1978 to 2004 of 0.07°C per year.” They state, “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 “also on West Greenland the period 1936–1946 was the warmest period within the last 106 years (Cappelen, 2004).”

“Using a set of 12 coastal and 40 inland ice surface air temperature records in combination with climate model output,” Box *et al.* (2009) reconstructed “long-term (1840–2007) monthly, seasonal, and annual spatial patterns of temperature variability over a continuous grid covering Greenland and the inland ice sheet,” after which they compared “the 1919–32 and 1994–2007 warming episodes” and made “a comparison of Greenland ice sheet surface air temperature temporal variability with that of the Northern Hemisphere average.” The near-surface air temperature history Box *et al.* derived for Greenland is reproduced in Figure 4.2.4.3.3.1.1, along with the corresponding history of Northern Hemispheric near-surface air temperature.

The four researchers determined “the annual whole ice sheet 1919–32 warming trend is 33% greater in magnitude than the 1994–2007 warming,” and “in contrast to the 1920s warming, the 1994–2007 warming has not surpassed the Northern Hemisphere anomaly.” They note “an additional 1.0°–1.5°C of annual mean warming would be needed for Greenland to be in phase with the Northern Hemisphere pattern.” The results of Box *et al.* demonstrate there is nothing unusual, unnatural, or unprecedented about the nature of Greenland’s 1994–2007 warming episode, when the atmosphere’s CO₂ concentration rose by about

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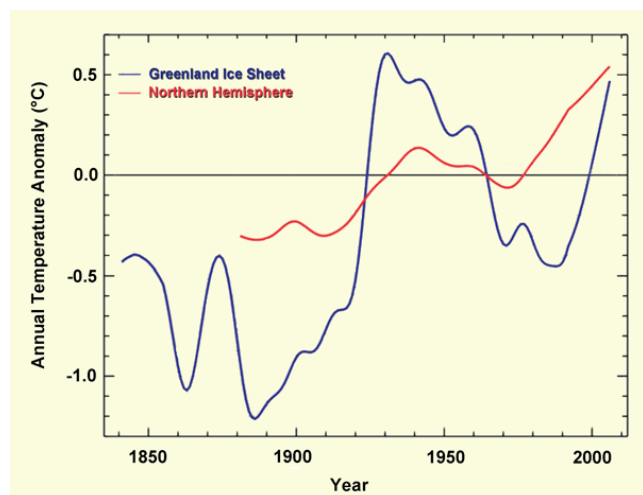


Figure 4.2.4.3.1.1. Low-pass-filtered Greenland and Northern Hemispheric near-surface air temperature anomalies with respect to the 1951–1980 base period vs. time. Adapted from Box, J.E., Yang, L., Bromwich, D.H., and Bai, L.-S. 2009. Greenland ice sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.

25 ppm, which is much less impressive than the 1919–1932 warming, when the atmosphere’s CO₂ concentration rose by about 5 ppm.

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- #### 4.2.4.3.3 Russia/Asian Arctic
- Zeeberg and Forman (2001) analyzed twentieth century changes in glacier terminus positions on north Novaya Zemlya, a Russian island located between the Barents and Kara Seas in the Arctic Ocean, providing a quantitative assessment of the effects of temperature and precipitation on glacial mass balance. This work revealed a significant and accelerated post-Little Ice Age glacial retreat in the first and second decades of the twentieth century, but by 1952, the region's glaciers had experienced 75–100% of their net twentieth century retreat. During the next 50 years the recession of more than half the glaciers stopped, and many tidewater glaciers began to advance.
- These glacial stabilizations and advances were attributed by the two scientists to observed increases in precipitation and/or decreases in temperature. In the four decades since 1961, for example, weather stations at Novaya Zemlya show summer temperatures to have been 0.3 to 0.5°C colder than they were over the prior 40 years, while winter temperatures were 2.3 to 2.8°C colder. Zeeberg and Forman say such observations are “counter to warming of the Eurasian Arctic predicted for the twenty-first century by climate models, particularly for the winter season.”
- Polyakov *et al.* (2002) used newly available long-term Russian observations of surface air temperature from coastal stations to gain new insights into trends and variability in the Arctic environment poleward of 62°N. Throughout the 125-year history they developed, they identified “strong intrinsic variability, dominated by multi-decadal fluctuations with a timescale of 60–80 years” and found temperature trends in the Arctic to be highly dependent on the particular time period selected for analysis. They found they could “identify periods when Arctic trends were actually smaller or of different sign than Northern Hemisphere trends.” Over the bulk of the twentieth century, however, when “multi-decadal variability had little net effect on computed trends,” the temperature histories of the two regions were “similar” but did “not support amplified warming in polar regions predicted by GCMs.”
- Raspopov *et al.* (2004) presented and analyzed two temperature-related datasets: “a direct and

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systematic air temperature record for the Kola Peninsula, in the vicinity of Murmansk,” which covered the period 1880–2000, and an “annual tree-ring series generalized for 10 regions (Lovelius, 1997) along the northern timberline, from the Kola Peninsula to Chukotka, for the period 1458–1975 in the longitude range from 30°E to 170°E,” which included nearly all of northern Eurasia that borders the Arctic Ocean. The researchers’ primary objectives were to identify any temporal cycles present in the two datasets and determine what caused them. They report discovering “climatic cycles with periods of around 90, 22–23 and 11–12 years,” which were found to “correlate well with the corresponding solar activity cycles.”

Of even more interest was what they learned about the temporal development of the Current Warm Period (CWP). Raspopov *et al.*’s presentation of the mean annual tree-ring series for the northern Eurasia timberline clearly shows the region’s recovery from the coldest temperatures of the Little Ice Age (LIA) may be considered to have commenced as early as 1820 and was in full swing by at least 1840. It shows the rising temperature peaked just prior to 1950 and then declined to the end of the record in 1975. The Kola-Murmansk instrumental record indicates a significant temperature rise that peaked in the early 1990s at about the same level as the pre-1950 peak but then declined to the end of the record in 2000.

The last of these findings—that there was no net warming of this expansive high-latitude region over the last half of the twentieth century—is in harmony with the findings of the many studies we have reviewed here. The first finding—that the thermal recovery of this climatically sensitive region of the planet began in the first half of the nineteenth century—is also supported by several other studies (Esper *et al.*, 2002; Moore *et al.*, 2002; Yoo and D’Odorico, 2002; Gonzalez-Rouco *et al.*, 2003; Jomelli and Pech, 2004). All demonstrate the Little Ice Age-to-Current Warm Period transition began somewhere in the neighborhood of 1820 to 1850, well before the date (~1910) indicated in the Mann *et al.* (1998, 1999) “hockey stick” temperature history promulgated by the IPCC.

This difference is important, for it indicates the LIA-to-CWP transition in the Arctic was likely halfway or more complete before the Mann *et al.* temperature history suggests it even began, demonstrating most of the transition occurred well in advance of anthropogenic-caused increases in CO₂ emissions. That there was no net warming between

somewhere in the 1930s or 1940s and the end of the twentieth century in the part of the world where CO₂-induced global warming is supposed to be most evident (the Arctic) makes it abundantly clear anthropogenic CO₂ emissions have had no discernible impact on any part of the LIA-to-CWP transition, the “global warming” some continue to claim is still occurring and can be stopped by reducing CO₂ emissions.

Groisman *et al.* (2006) write, “a new Global Synoptic Data Network consisting of 2100 stations within the boundaries of the former Soviet Union created jointly by the [U.S.] National Climatic Data Center and Russian Institute for Hydrometeorological Information was used to assess the climatology of snow cover, frozen and unfrozen ground reports, and their temporal variability for the period from 1936 to 2004.” They determined “during the past 69 years (1936–2004 period), an increase in duration of the period with snow on the ground over Russia and the Russian polar region north of the Arctic circle has been documented by 5 days or 3% and 12 days or 5%, respectively,” and they note this result “is in agreement with other findings.”

Commenting on this development and the similar findings of others, the five researchers state, “changes in snow cover extent during the 1936–2004 period cannot be linked with ‘warming’ (particularly with the Arctic warming)” because “in this particular period the Arctic warming was absent.”

Opel *et al.* (2009) worked with the uppermost 57 meters of a surface-to-bedrock ice core retrieved from the Akademii Nauk (AN) ice cap (~80°31’N, 94°49’E) of the Severnaya Zemlya archipelago (located in the central Russian Arctic between the Kara and Laptev Seas) to derive a $\delta^{18}\text{O}$ history covering the period 1883–1998. They compared this history with surface air temperatures (SATs) measured at 15 weather stations distributed throughout the Atlantic and Eurasian sub-Arctic, finding “good correlations and similarities.” They note their $\delta^{18}\text{O}$ data also had “a strong correlation with the composite Arctic (north of 62° N) SAT anomalies time series of Polyakov *et al.* (2003),” demonstrating their $\delta^{18}\text{O}$ data can serve as a proxy for the region’s SAT. They found “the $\delta^{18}\text{O}$ values show pronounced 20th-century temperature changes, with a strong rise about 1920 and the absolute temperature maximum in the 1930s.” As shown in Figure 4.2.4.3.3.1, there was no net warming of the Atlantic and Eurasian sub-Arctic over the last 80 years of the twentieth century.

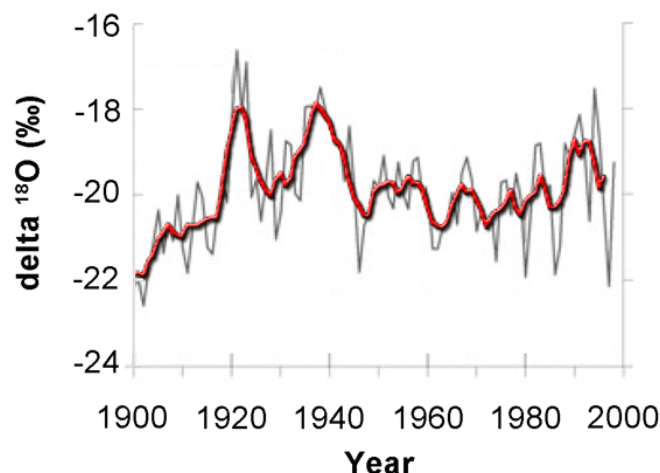


Figure 4.2.4.3.3.1. $\delta^{18}\text{O}$ (‰) vs. time (Years AD). Adapted from Opel, T., Fritzsche, D., Meyer, H., Schutt, R., Weiler, K., Ruth, U., Wilhelms, F., and Fischer, H. 2009. 115 year ice-core data from Akademii Nauk ice cap, Severnaya Zemlya: high-resolution record of Eurasian Arctic climate change. *Journal of Glaciology* **55**: 21–31.

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4.2.4.3.3.4 Scandinavia and Iceland

Humlum *et al.* (2005) note state-of-the-art climate models predict “the effect of any present and future global climatic change will be amplified in the polar regions as a result of feedbacks in which variations in the extent of glaciers, snow, sea ice and permafrost, as well as atmospheric greenhouse gases, play key roles.” They also note Polyakov *et al.* (2002a,b) “presented updated observational trends and variations in Arctic climate and sea-ice cover during the twentieth century, which do not support the modeled polar amplification of surface air-temperature changes observed by surface stations at lower latitudes,” and “there is reason, therefore, to

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evaluate climate dynamics and their respective impacts on high-latitude glaciers.” They proceeded to do so for the Archipelago of Svalbard, focusing on Spitsbergen (the Archipelago’s main island) and the Longyearbreen glacier located in its relatively dry central region at 78°13’N latitude.

Humlum *et al.* report, “a marked warming around 1920 changed the mean annual air temperature (MAAT) at sea level within only 5 years from about -9.5°C to -4.0°C,” which “represents the most pronounced increase in MAAT documented anywhere in the world during the instrumental period.” Then, they report, “from 1957 to 1968, MAAT dropped about 4°C, followed by a more gradual increase towards the end of the twentieth century.”

Their work reveals the Longyearbreen glacier “increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years” and they state, “this example of late-Holocene glacier growth represents a widespread phenomenon in Svalbard and in adjoining Arctic regions,” which they describe as a “development towards cooler conditions in the Arctic,” which “may explain why the Little Ice Age glacier advance in Svalbard usually represents the Holocene maximum glacier extension.”

Temperatures in Svalbard rose more rapidly in the early 1920s than has been documented anywhere else before or since, only to be followed by a nearly equivalent temperature drop four decades later, both of which were out of line with what climate models suggest should have occurred. The current location of the terminus of the Longyearbreen glacier suggests, even now, Svalbard and “adjoining Arctic regions” are still experiencing some of the lowest temperatures of the entire Holocene, at a time when atmospheric CO₂ concentrations are higher than they likely have been for millions of years. These observations are also at odds with what the IPCC claims about the strong warming power of rising atmospheric CO₂. There is little reason to put much confidence in the IPCC’s claims, or to get too excited if the Arctic were to warm a bit—or even substantially and at a rapid rate. It has done so before, and it likely will do so again.

Hanna *et al.* (2006) developed a 119-year history of Icelandic Sea Surface Temperature (SST) based on measurements made at ten coastal stations located between latitudes 63°24’N and 66°32’N. This work revealed the existence of past “long-term variations and trends that are broadly similar to Icelandic air temperature records: that is, generally cold conditions during the late nineteenth and early twentieth

centuries; strong warming in the 1920s, with peak SSTs typically being attained around 1940; and cooling thereafter until the 1970s, followed once again by warming—but not generally back up to the level of the 1930s/1940s warm period.”

This brief section concludes with a short synopsis of a brief communication from Karlen (2005), in which he asks whether temperatures in the Arctic are “really rising at an alarming rate,” as the models suggest they should be doing. His short answer is a resounding no; his explanation follows.

Focusing on Svalbard Lufthavn (located at 78°N latitude), which he later showed to be representative of much of the Arctic, Karlen reports “the Svalbard mean annual temperature increased rapidly from the 1910s to the late 1930s”; “the temperature thereafter became lower, and a minimum was reached around 1970”; and “Svalbard thereafter became warmer, but the mean temperature in the late 1990s was still slightly cooler than it was in the late 1930s,” indicative of an actual cooling trend of 0.11°C per decade over the last 70 years of the twentieth century.

In support of his contention that cooling was the norm in the Arctic over this period, Karlen states “the observed warming during the 1930s is supported by data from several stations along the Arctic coasts and on islands in the Arctic, e.g. *Nordklim* data from Bjornoya and Jan Mayen in the north Atlantic, Vardo and Tromso in northern Norway, Sodankylae and Karasjoki in northern Finland, and Stykkisholmur in Iceland.” He also notes “there is also [similar] data from other reports; e.g. Godthaab, Jakobshavn, and Egedesminde in Greenland, Ostrov Dikson on the north coast of Siberia, Salehard in inland Siberia, and Nome in western Alaska.” All of these stations “indicate the same pattern of changes in annual mean temperature: a warm 1930s, a cooling until around 1970, and thereafter a warming, although the temperature remains slightly below the level of the late 1930s.” In addition, “many stations with records starting later than the 1930s also indicate cooling, e.g. Vize in the Arctic Sea north of the Siberian coast and Frobisher Bay and Clyde on Baffin Island.” Karlen reports the 250-year temperature record of Stockholm “shows that the fluctuations of the 1900s are not unique” and “changes of the same magnitude as in the 1900s occurred between 1770 and 1800, and distinct but smaller fluctuations occurred around 1825.”

Noting the IPCC suggests the lion’s share of the temperature increase during the 1920s and into the 1930s, which in the Arctic was the most dramatic warming of the twentieth century, was primarily due

to solar effects (because the increase in CO₂ over this period was so small they had to go with something else), Karlen points out, “during the 50 years in which the atmospheric concentration of CO₂ has increased considerably, the temperature has decreased,” which leads him to conclude “the Arctic temperature data do not support the models predicting that there will be a critical future warming of the climate because of an increased concentration of CO₂ in the atmosphere.” As the first and only period of net warming in the Arctic occurred at a time when CO₂ could not have been its cause, it should be clear the modern theory of CO₂-induced global warming is an unreliable guide to the future.

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- 4.2.4.3.3.5 The Rest of the Arctic/Multiple Regions
- Przybylak (2000) used mean monthly temperatures measured at 37 Arctic and 7 sub-Arctic stations, as well as temperature anomalies of 30 grid-boxes obtained from the updated dataset of Jones, to derive a number of spatial and temporal histories of Arctic near-surface air temperature. These analyses led the author to conclude, “In the Arctic, the highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s.” He reports, “even in the 1950s the temperature was higher than in the last 10 years”; “since the mid-1970s, the annual temperature shows no clear trend”; and “the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century.” Przybylak concludes, “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.”
- Two years later in a similar analysis, Przybylak (2002) examined intraseasonal (within season) and interannual (between years) variability in maximum, minimum, and average air temperature and diurnal air temperature range for the entire Arctic, as delineated by Treshnikov (1985), for the period 1951–1990, based on data from ten stations “representing the majority of the climatic regions in the Arctic.” He found “trends in both the intraseasonal and interannual variability of the temperatures studied did not show any significant changes,” leading Przybylak to conclude “this aspect of climate change, as well as trends in average seasonal and annual values of temperature investigated earlier (Przybylak, 1997, 2000), proves that, in the Arctic in the period 1951–90, no tangible manifestations of the greenhouse effect can be identified.”
- Polyakov *et al.* (2003) derived a surface air temperature history that stretched from 1875 to 2000, based on measurements carried out at 75 land stations and a number of drifting buoys located poleward of 62°N latitude. From 1875 to about 1917, the team of eight U.S. and Russian scientists found the surface air temperature of the northern region rose hardly at all, but then it climbed 1.7°C in just 20 years to reach a peak in 1937 that was not eclipsed over the remainder of the record. During this 20-year period of rapidly rising air temperature, the atmosphere’s CO₂ concentration rose by a mere 8 ppm. Over the next six decades, when the air’s CO₂ concentration rose by approximately 55 ppm—nearly seven times more than it had during the 20-year period of dramatic warming that preceded it—the surface air temperature of the region poleward of 62°N experienced no net warming and may have cooled.
- Polyakov *et al.* (2004) developed a long-term

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history of Atlantic Core Water Temperature (ACWT) in the Arctic Ocean using high-latitude hydrographic measurements initiated in the late nineteenth century. They compared this history with the long-term history of Arctic Surface Air Temperature (SAT) developed a year earlier by Polyakov *et al.* (2003). The ACWT record revealed the existence of “two distinct warm periods from the late 1920s to 1950s and in the late 1980s–90s and two cold periods, one at the beginning of the record (until the 1920s) and another in the 1960s–70s.” The SAT record depicted essentially the same thing, with the peak temperature of the latter warm period being not quite as high as the peak temperature of the former warm period. In the case of the ACWT record, this relationship was reversed, with the peak temperature of the latter warm period slightly exceeding the peak temperature of the former warm period. The most recent temperature peak was very short-lived and it rapidly declined, ending approximately 1°C cooler over the last few years of the record.

Like Arctic SATs, Arctic ACWTs are dominated “by multidecadal fluctuations with a time scale of 50–80 years,” Polyakov *et al.* write. Both records indicate late twentieth century warmth was no different from that experienced in the late 1930s and early 1940s, offering no compelling reason to believe late twentieth century warmth was the result of CO₂-induced global warming, for the air’s CO₂ concentration in the late 1930s and early 1940s was fully 80 ppm less than it is today.

Soon (2005) sought to determine whether rising atmospheric CO₂ concentration or variations in solar irradiance was the more dominant driver of twentieth century temperature change in the Arctic. He examined the roles the two variables may have played in forcing decadal, multi-decadal, and longer-term variations in surface air temperature (SAT), performing statistical analyses on a composite Arctic-wide SAT record constructed by Polyakov *et al.* (2003), global CO₂ concentrations taken from estimates made by the NASA GISS climate modeling group, and a total solar irradiance (TSI) record developed by Hoyt and Schatten (1993, updated by Hoyt in 2005) over the period 1875–2000.

Soon’s analyses show a much stronger statistical relationship between SAT and TSI than between SAT and atmospheric CO₂ concentration. Solar forcing generally explained more than 75 percent of the variance in decadal-smoothed seasonal and annual Arctic temperatures, whereas CO₂ forcing explained only between 8 and 22 percent. Wavelet analysis

further supported the case for solar forcing of SAT, revealing similar time-frequency characteristics for annual and seasonally averaged temperatures at decadal and multi-decadal time scales. In contrast, wavelet analysis gave little to no indication of a CO₂ forcing of Arctic SSTs. It would appear the Sun, not atmospheric CO₂, drove temperature change in the Arctic over the twentieth century.

Chylek *et al.* (2009) write, “one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback.” They note “the surface air temperature change in the Arctic is predicted to be about two to three times the global mean,” citing the IPCC (2007). Utilizing Arctic surface air temperature data from 37 meteorological stations north of 64°N, Chylek *et al.* explored the latitudinal variability in Arctic temperatures within two latitude belts—the low Arctic (64°N–70°N) and the high Arctic (70°N–90°N)—comparing the results with the mean measured air temperatures of these two regions over three periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

In initial apparent harmony with state-of-the-art AOGCM simulations, the five researchers report “the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean.” The Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that was the end of the real world’s climate-change agreement with theory. During the 1910–1940 warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic.

These findings constitute yet another important example of the principle described and proven by Reifen and Toumi (2009): A model that performs well in one time period will not necessarily perform well in another time period. Since AOGCMs suffer from this shortcoming, they ought not be considered adequate justification for imposing dramatic cuts in anthropogenic CO₂ emissions, as their simulations of future temperature trends may be far different from what will actually transpire.

Ladd and Gajewski (2010) evaluated the position of the Arctic front—defined as “the semi-permanent,

discontinuous front between the cold Arctic air mass and the intermediate Polar air mass, bounded in the south by the Polar Front (Oliver and Fairbridge, 1987)—based on gridded data obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis (NNR) for each July between 1948 and 2007, and from 1958 to 2002 using data from the European Centre for Medium-Range Weather Forecasts ERA-40, as well as the period 1948–1957 “for comparison with the results of Bryson (1966).” The two researchers report “the position of the July Arctic front varies significantly through the period 1948–2007,” but they find it does so “with a mean position similar to that found by Bryson (1966),” which “close similarity is striking,” they say, “given that the Bryson study was completed over 40 years ago.”

Wood and Overland (2010) note “the recent widespread warming of the Earth’s climate is the second of two marked climatic fluctuations to attract the attention of scientists and the public since the turn of the 20th century,” and the first of these—“the major early 20th century climatic fluctuation (~1920–1940)—has been “the subject of scientific enquiry from the time it was detected in the 1920s.” They write “the early climatic fluctuation is particularly intriguing now because it shares some of the features of the present warming that has been felt so strongly in the Arctic.” Wood and Overland reviewed what is known about the first warming through “a rediscovery of early research and new assessments of the instrumental record,” which allowed them to compare what they learned about the earlier warming with what is known about the most recent one.

With respect to the first of the two warmings, the U.S. researchers say “there is evidence that the magnitude of the impacts on glaciers and tundra landscapes around the North Atlantic was larger during this period than at any other time in the historical period.” In addition, “the ultimate cause of the early climatic fluctuation was not discovered by early authors and remains an open question,” noting “all of the leading possibilities recognized today were raised by the 1950s, including internal atmospheric variability, anthropogenic greenhouse gas (CO₂) forcing, solar variability, volcanism, and regional dynamic feedbacks (e.g. Manley, 1961).” They add, “greenhouse gas forcing is not now considered to have played a major role (Hegerl *et al.*, 2007).” Thus, they suggest “the early climatic fluctuation was a singular event resulting from intrinsic variability in the large-scale atmosphere/ocean/land system and that

it was likely initiated by atmospheric forcing.”

Wood and Overland conclude the “early climatic fluctuation is best interpreted as a large but random climate excursion imposed on top of the steadily rising global mean temperature associated with anthropogenic forcing.” However, the early warming also could be interpreted as a large but random climate excursion imposed on top of the steadily rising global mean temperature associated with Earth’s natural recovery from the global chill of the Little Ice Age. And there is no reason not to conclude the same about the most recent Arctic warming; in a major analysis of past rates of climate change in the Arctic, White *et al.* (2010) conclude, “thus far, human influence does not stand out relative to other, natural causes of climate change.”

Wood *et al.* (2010) constructed a two-century (1802–2009) instrumental record of annual surface air temperature within the Atlantic-Arctic boundary region, using data obtained from “recently published (Klingbejer and Moberg, 2003; Vinther *et al.*, 2006) and historical sources (Wahlen, 1886)” that yielded “four station-based composite time series” pertaining to Southwestern Greenland, Iceland, Tornedalen (Sweden), and Arkhangel’sk (Russia). This added 76 years to the previously available record. The credibility of their results, Wood *et al.* note, “is supported by ice core records, other temperature proxies, and historical evidence.”

The U.S. and Icelandic researchers report the newly extended temperature history and their analysis of it reveal “an irregular pattern of decadal-scale temperature fluctuations over the past two centuries,” of which the early twentieth century warming (ETCW) event—which they say “began about 1920 and persisted until mid-century”—was by far “the most striking historical example.” Wood *et al.* write, “as for the future, with no other examples in the record quite like the ETCW, we cannot easily suggest how often—much less when—such a comparably large regional climate fluctuation might be expected to appear.” Nevertheless, they state, “it would be reasonable to expect substantial regional climate fluctuations of either sign to appear from time to time” and, therefore, “singular episodes of regional climate fluctuation should be anticipated in the future.” This conclusion also implies any rapid warming that may subsequently occur within the Atlantic-Arctic boundary region need not be due to rising greenhouse gas concentrations, as it could be caused by the same factor that caused the remarkable ETCW event.

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4.2.4.4 Asia

As indicated in the introduction of Section 4.2.4, numerous peer-reviewed studies reveal modern temperatures are not unusual, unnatural, or unprecedented. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO₂ concentration. This reality is further illustrated by the fact that 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 today's.

The following subsections highlight such research from Asia, 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 believe it is having any measurable impact on climate today.

4.2.4.4.1 China

Using a variety of climate records derived from peat, lake sediment, ice core, tree-ring, and other proxy sources, Yang *et al.* (2002) identified a period of exceptional warmth throughout China between AD 800 and 1100. Yafeng *et al.* (1999) also observed a warm period between AD 970 and 1510 in $\delta^{18}\text{O}$ data obtained from the Guliya ice cap of the Qinghai-Tibet Plateau, while Hong *et al.* (2000) developed a 6,000-year $\delta^{18}\text{O}$ record from plant cellulose deposited in a peat bog in the Jilin Province (42° 20' N, 126° 22' E), within which they found evidence of “an obvious warm period represented by the high $\delta^{18}\text{O}$ from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe” (see Figure 4.2.4.4.1.1).

Hong *et al.* (2000) had previously reported that at the time of the MWP, “the northern boundary of the cultivation of citrus tree (*Citrus reticulata* Blanco) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, where it has been estimated that the annual mean temperature was 0.9–1.0°C higher than at present.” Considering the climatic conditions required to successfully grow these plants, they further note annual mean temperatures in that part of the country during the Medieval Warm Period must have been about 1.0°C higher than at present, with extreme January minimum temperatures fully 3.5°C warmer than they are today, citing De'er (1994).

Xu *et al.* (2002) also determined, from a study of plant cellulose $\delta^{18}\text{O}$ variations in cores retrieved from peat deposits at the northeastern edge of the Qinghai-Tibet Plateau, from AD 1100–1300 “the $\delta^{18}\text{O}$ of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the ‘Medieval Warm Period.’” Qian and Zhu (2002) analyzed the thickness of laminae in a stalagmite found in Shihua Cave, Beijing, from which they inferred the existence of a relatively wet period from approximately AD 940 to 1200.

Chu *et al.* (2002) studied the geochemistry of 1,400 years of dated sediments recovered from seven

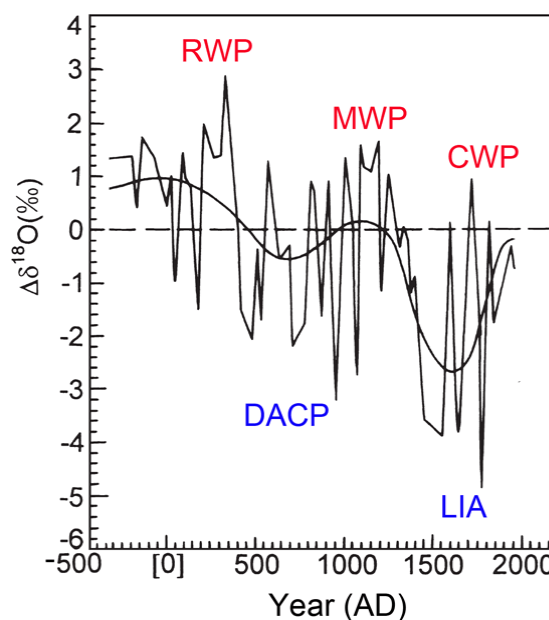


Figure 4.2.4.4.1.1. A 6,000-year $\delta^{18}\text{O}$ record from a peat bog in the Jilin Province. Adapted from Hong, Y.T., Jiang, H.B., Liu, T.S., Zhou, L.P., Beer, J., Li, H.D., Leng, X.T., Hong, B., and Qin, X.G. 2000. Response of climate to solar forcing recorded in a 6000-year $\delta^{18}\text{O}$ time-series of Chinese peat cellulose. *The Holocene* 10: 1–7.

cores taken from three locations in Lake Huguangyan (21°9'N, 110°17'E) on the low-lying Leizhou Peninsula in the tropical region of South China, together with information about the presence of snow, sleet, frost, and frozen rivers over the past 1,000 years obtained from historical documents. They note “recent publications based on the phenological phenomena, distribution patterns of subtropical plants and cold events (Wang and Gong, 2000; Man, 1998; Wu and Dang, 1998; Zhang, 1994) argue for a warm period from the beginning of the tenth century AD to the late thirteenth century AD,” as their own data also suggest. In addition, they note there was a major dry period from AD 880–1260, and “local historical chronicles support these data, suggesting the climate of tropical South China was dry during the ‘Mediaeval Warm Period.’”

In an analysis of past sea-level history in the South China Sea, Zicheng *et al.* (2003) cite the work of Honghan and Baolin (1996, in Chinese), stating these authors found “the climate temperature at 1000 a B.P. is 1–2°C higher than that at present time,” referring to the Futian section on the eastern bank of the Pearl River, Shenzhen Bay, China (~22.5°N, 113.5°E). Zicheng *et al.* also cited the work of Baofu

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et al. (1997), who investigated palaeotemperatures of the coral reef at Denglouliao, Leizhou Peninsula, China (~20.25°N, 110°E) and report “sea-surface temperature at 1170 a.B.P. is 2°C higher than that at present time.”

Paulsen *et al.* (2003) used high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data derived from a stalagmite found in Buddha Cave (33°40'N, 109°05'E) to infer changes in climate in central China over the prior 1,270 years. Among the climatic episodes evident in their data were, they write, “those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events.” The dry-then-wet-then-dry-again MWP began about AD 965 and continued to approximately AD 1475.

Ma *et al.* (2003) analyzed a stalagmite from Jingdong Cave, about 90 km northeast of Beijing, to assess the climatic history of the past 3,000 years at 100-year intervals on the basis of $\delta^{18}\text{O}$ data, the Mg/Sr ratio, and the solid-liquid distribution coefficient of Mg. The researchers found between 200 and 500 years ago “air temperature was about 1.2°C lower than that of the present,” but between 1,000 and 1,300 years ago, there was an equally aberrant but warm period that “corresponded to the Medieval Warm Period in Europe.”

Based on 200 sets of phenological and meteorological records extracted from a variety of historical sources, many of which are described by Gong and Chen (1980), Man (1990, 2004), Sheng (1990), and Wen and Wen (1996), Ge *et al.* (2003) produced a 2,000-year history of winter half-year temperature (October to April, when CO₂-induced global warming is projected to be most evident) for the region of China bounded by latitudes 27 and 40°N and longitudes 107 and 120°E. This work revealed a significant warm epoch from the AD 570s to the 1310s, the peak warmth of which was “about 0.3–0.6°C higher than present for 30-year periods, but over 0.9°C warmer on a 10-year basis” (see Figure 4.2.4.4.1.2).

Zhu *et al.* (2003) worked with a sediment core extracted from lake Chen Co in the Yamzhog Yum Co drainage basin of southern Tibet in the delta of the Kaluxiong River, dated by comparing sedimentary rates measured by ^{210}Pb and absolute time horizons measured by ^{137}Cs (Wan 1997, 1999; Benoit and Rozan, 2001). Several environmentally related magnetic properties of sections of the core were measured and analyzed. This work revealed a “Middle Ages Warm-period” (around ca. 1120–1370 AD) followed by “an intensively cold stage during ca. 1550–1690 AD, a cold-humid stage from ca. 1690–1900 AD and a warm-dry stage since ca. 1900 AD.” They note the warm period of the past century was not as warm as the earlier 250-year warm period of the Middle Ages.

Bao *et al.* (2003) utilized proxy climate records (ice-core $\delta^{18}\text{O}$, peat-cellulose $\delta^{18}\text{O}$, tree-ring widths,

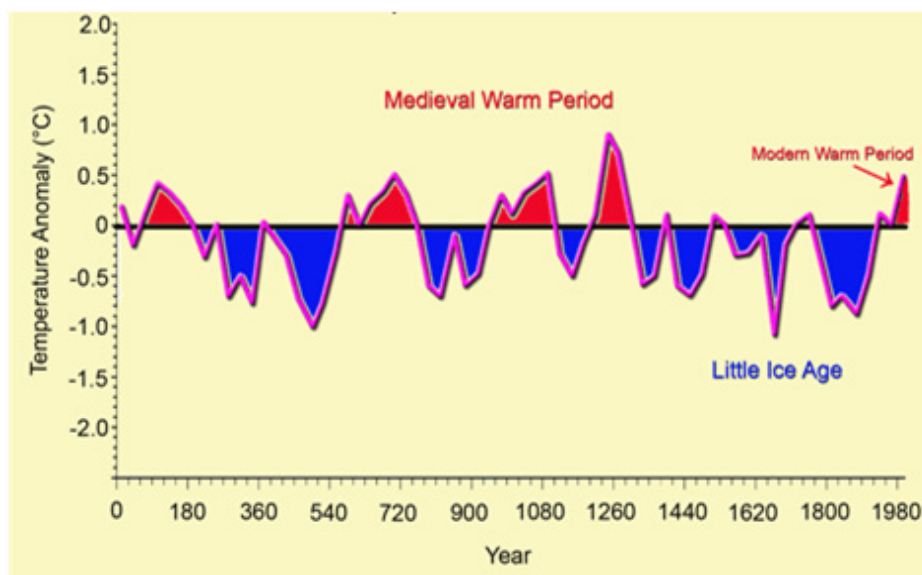


Figure 4.2.4.4.1.2. Winter half-year temperature anomalies for eastern China. Adapted from Ge, Q., Zheng, J., Fang, X., Man, Z., Zhang, X., Zhang, P., and Wang, W.-C. 2003. Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. *The Holocene* 13: 933–940.

tree-ring stable carbon isotopes, total organic carbon, lake water temperatures, glacier fluctuations, ice-core CH₄, magnetic parameters, pollen assemblages, and sedimentary pigments) obtained from 20 prior studies to derive a 2,000-year temperature history of the northeastern, southern, and western sections of the Tibetan Plateau. In each case, there was more than one prior 50-year period when the mean temperature of each region was warmer than it was over the most

recent 50-year period. In the case of the northeastern sector of the plateau, all of the maximum-warmth intervals occurred during the Medieval Warm Period; in the western sector, they occurred near the end of the Roman Warm Period; and in the southern sector they occurred during both warm periods. With respect to the entire Tibetan Plateau, the researchers found nothing extraordinary about the recent past. For the whole region, there was one prior 50-year period when temperatures were warmer than they were over the most recent 50-year period, and that was near the end of the Roman Warm Period, some 1850 years ago.

Bao *et al.* (2004) collected and analyzed proxy climate data derived from ice cores, tree rings, river and lake sediments, and lake terraces and paleosols, as well as historical documents, to determine the climatic state of northwest China during the Western and Eastern Han Dynasties (206 BC–AD 220) relative to the past two millennia. Their analysis revealed “strong evidence for a relatively warm and humid period in northwest China between 2.2 and 1.8 kyr BP,” during the same time interval as the Roman Warm Period, which period experienced higher temperatures than those of today. They note “the warm-wet climate period during 2.2–1.8 kyr BP also occurred in central and east China, after [which] temperatures decreased rapidly (Zhu, 1973; Hameed and Gong, 1993; Yan *et al.*, 1991, 1993; Shi and Zhang, 1996; Ge *et al.*, 2002).” They found historical records report “an abrupt climate change from warmer and wetter to cooler and drier conditions occurred around AD 280 (Zhang *et al.*, 1994).” In addition, “three alternate China-wide temperature composites covering the last 2000 years display an obvious warm stage in 0–240 AD (Yang *et al.*, 2002),” and “according to a 2650-year warm-season temperature reconstruction from a stalagmite from Shihua Cave of Beijing (Tan *et al.*, 2003), the temperatures during 2.1–1.8 ka BP were basically above the average of the entire temperature series.”

Bao *et al.* conclude, “the warm and moist conditions during the Western and Eastern Han Dynasties [i.e., the Roman Warm Period] might have been responsible for the large-scale agricultural production and the local socioeconomic boom that is documented by the occurrence of the famous ruin groups of Loulan, Niya, and Keriya.” Citing the existence of plant remains such as walnuts, rice, barley, millet, and wheat grains found in the area, they also indicate the water and temperature conditions of the Roman Warm Period “were suitable

for rice cultivation and much better than today.”

Wei *et al.* (2004) measured high-resolution Sr/Ca ratios in two *Porites* corals off the coast of the Leizhou Peninsula in the northern South China Sea, using inductively coupled plasma atomic spectrometry, and their ages were determined via U-Th dating. The transfer function relating the Sr/Ca ratio to temperature was established on a modern *Porites lutea* coral by calibrating against sea surface temperatures (SSTs) measured from 1989 to 2000 at the nearby Haikou Meteorological Station. By these means one of the two coral sections was dated to AD 489–500 in the middle of the Dark Ages Cold Period, and the other was dated to 539–530 BC in the middle of the Roman Warm Period.

From the Dark Ages Cold Period portion of the coral record, Wei *et al.* determined the average annual SST was approximately 2.0°C colder than that of the last decade of the twentieth century (1989–2000), and from the Roman Warm Period portion of the record they obtained a mean annual temperature identical to that of the 1989–2000 period as measured at the Haikou Meteorological Station.

Yu *et al.* (2005) also derived high-resolution Sr/Ca ratios for *Porites lutea* coral samples taken off the coast of the Leizhou Peninsula and determined their ages by means of U-Th dating, and the transfer function relating the Sr/Ca ratio to temperature was obtained from a modern *P. lutea* coral in the same location by calibrating the ratio against SSTs measured from 1960 to 2000 at the Haikou Ocean Observatory. The researchers found the coral Sr/Ca ratio to be “an ideal and reliable thermometer,” after which they employed it to reveal a coral sample dated to ~541 BC during the Roman Warm Period yielded “a mean of Sr/Ca-SST maxima of 29.3°C and a mean of Sr/Ca-SST minima of 19.5°C, similar to those of the 1990s (the warmest period of the last century).” Yu *et al.* say “historic records show that it was relatively warm and wet in China during 800–300 BC (Eastern Zhou Dynasty),” noting “it was so warm during the early Eastern Zhou Dynasty (770–256 BC) that rivers in today’s Shangdong province (35–38°N) never froze for the whole winter season in 698, 590, and 545 BC.”

Zhang *et al.* (2004) reconstructed the salinity history of Qinghai Lake (the largest inland saline lake in China) for the period AD 1100–2000 based on a relationship between the shell length of the ostracod *Limnocythere inopinata* and the salinity of the water in which it lives, a relationship developed by Yin *et al.* (2001) from data gathered from 50 lakes of

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different salinities scattered across the Tibetan Plateau. Zhang *et al.* used ostracod shell-length data derived from a 114-cm sediment core to discover “low salinity during 1160–1290 AD showed the humid climate condition [of] the Medieval Warm Period in this area, while the high salinity during 1410–1540 AD, 1610–1670 AD and 1770–1850 AD [prevailed during] the three cold pulses of the Little Ice Age with a dry climate condition,” where the evidence for the occurrence of these warm and cold intervals came from the climate change studies of Yao *et al.* (1990) and Wang (2001).

Qinghai Lake’s modern salinity has not reached even the halfway point between the near-record high salinity of the last cold extreme of the Little Ice Age and the record low salinity experienced during the Medieval Warm Period, suggesting the warmth recently experienced in this region of China is nowhere near that experienced during the Medieval Warm Period. The salinity drop marking the “beginning of the end” of the last stage of the Little Ice Age began sometime prior to 1850, in harmony with the Northern Hemisphere temperature history of Esper *et al.* (2002) but in striking contradiction of the Northern Hemisphere temperature history of Mann *et al.* (1998, 1999), which does not depict any increase in temperature until after 1910, some 60 years later.

Ji *et al.* (2005) applied reflectance spectroscopy to a sediment core taken from the southeastern basin of Qinghai Lake. Sediment redness, related to iron oxide content, was judged to be an indicator of paleoclimatic changes in the core. Lower redness values were found to correlate with light, laminated sediments “associated with cold periods including the Little Ice Age (LIA),” whereas “warm periods, e.g., Medieval Warm Period (MWP), ... were marked by the accumulation of reddish-colored sediments.” Based upon these findings the MWP is observed to have been a long warm and wet period (AD 400–1200) sandwiched between the cold and dry spells of the Dark Ages Cold Period (100 BC–200 AD) and Little Ice Age (AD 1220–1600) (see Figure 4.2.4.4.1.3).

Liu *et al.* (2006a) developed a quantitative reconstruction of temperature changes over the past 3,500 years based on alkenone distribution patterns in a sediment core retrieved from Qinghai Lake, based on the alkenone unsaturation index ($U^{k'37}$) and its simplified form (U^{k37}), which they say “have been calibrated to growth temperatures of marine alkenone producers (Prahl *et al.*, 1988)” and “to temperature changes in lacustrine settings on a regional scale (Chu

et al., 2005; Zink *et al.*, 2001).” They state their temperature record “based on $U^{k'37}$ clearly shows oscillating warm/cold periods,” with periods at 0–200 yr BP, 500–1,100 yr BP, and 1,500–2,000 yr BP that were relatively warm and “could be related to the 20th-century warm period, the Medieval Warm Period, and the Roman Warm Period,” and “cold periods at 200–500 yr BP and 1100–1500 yr BP [that] corresponded to the Little Ice Age and the Dark Ages Cold Period.” In addition, their data indicate the peak warmth of the Roman Warm Period exceeded the temperature of the latter part of the twentieth century by about 0.4°C, and the peak warmth of the Medieval Warm Period exceeded the temperature of the latter part of the twentieth century by nearly 1°C. The existence of this millennial-scale oscillation of climate, with its prior periods of higher-than-current temperatures, clearly demonstrates there is nothing unusual about Earth’s present climatic state.

Ge *et al.* (2004) introduce their study of two thousand years of reconstructed winter half-year temperatures of eastern China by stating, “it is important to study the temperature change during the past 2000 years for understanding the issues such as the greenhouse effect and global warming induced by human activities.” They also note “China has advantages in reconstructing historical climate change for its abundant documented historical records and other natural evidence obtained from tree rings, lake sediments, ice cores, and stalagmites.”

The five climate scientists found “an about 1350-year periodicity in the historical temperature change,” which revealed a number of multi-century warm and cold periods. Preceding the Current Warm Period, for example, was the Little Ice Age (LIA), which “in China, began in the early 14th century (the 1320s) and ended in the beginning of the 20th century (the 1910s).” It included four cold stages and three short warming phases. The LIA, in turn, was preceded by the Medieval Warm Period, which Ge *et al.* say “began in the 930s and ended in the 1310s.” It was composed of two warm stages, each of more than 100 years duration, and a shorter intervening cold stage.

Looking further back in time, the Chinese scientists found a cold period from the 780s to the 920s and a warm period from the 570s to the 770s, which was in turn preceded by a cold period from the 210s to the 560s, which they say “was the only one comparable with [the] LIA for the past 2000 years.” This ultra-cold spell was the Dark Ages Cold Period that followed on the heels of the Roman Warm Period.

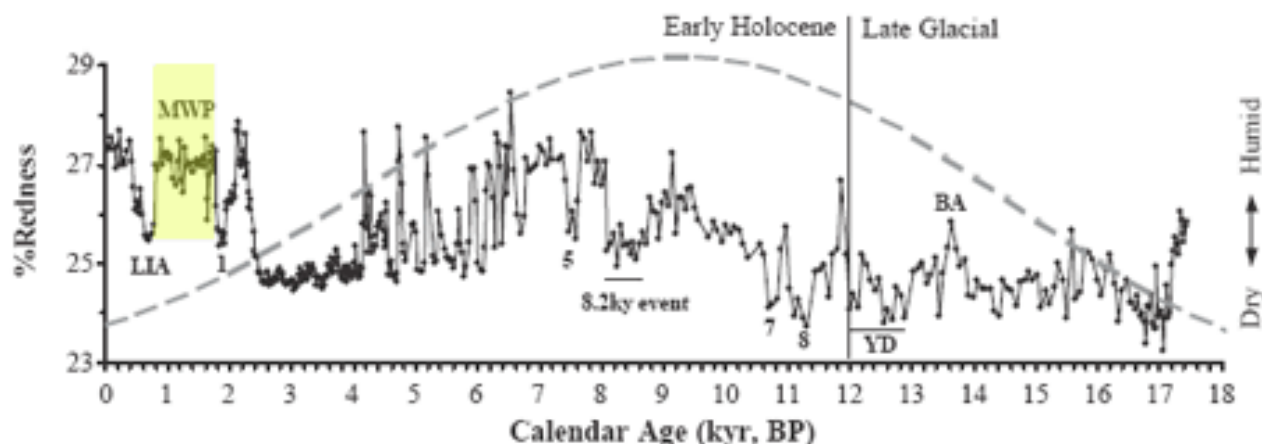


Figure 4.2.4.1.3. Qinghai Lake climate proxy showing the presence of the Little Ice Age and Medieval Warm Period as determined by the % redness value in a lake sediment core. Adapted from Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L., and Liu, X. 2005. Asian monsoon oscillations in the northeastern Qinghai-Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters* **233**: 61–70.

Ge *et al.* state one of the purposes of their study was “to test whether the warming in the 20th century has exceeded the maximum magnitude in the past 2000 years.” At the centennial scale, they report, “the temperature anomaly of the 20th century is not only lower than that of the later warm stage of the Medieval Warm Period (the 1200s~1310s), but also slightly lower than that of the warm period in the Sui and Tang dynasties (the 570s~770s) and the early warm stage of the Medieval Warm Period (the 930s~1100s).”

On a 30-year scale, they report, “the warmest 30-year temperature anomaly in the 20th century is roughly equal to the warmest 30-year one in the Sui and Tang dynasties warm period, but a little lower than that of the Medieval Warm Period.” On the decadal scale, they note “the warmest decadal temperature anomaly in the 20th century is approximately at the same level of the warmest decade of the early stage of the Medieval Warm Period.”

Ge *et al.* find “although the warming rate in the early 20th century has reached 1.1°C per century, such a rapid change is not unique during the alternation from the cold period[s] to the warm period[s]” of the prior 2,000 years. For example, they report the per-century warming rate from the 480s~500s to the 570s~590s was 1.3°C, from the 1140s~1160s to the 1230s~1250s was 1.4°C, and from the 1650s~1670s to the 1740s~1760s was 1.2°C.

Ge *et al.* say their analysis “gives a different viewpoint from that ‘the 20th century is the warmest century in the past 1000 years’, presented by IPCC, and is of great significance for better understanding the phenomena of the greenhouse effect and global warming etc. induced by human activities.” With respect to what that “different viewpoint” might be, Ge *et al.* state it is that “the temperature of the 20th century in eastern China is still within the threshold of the variability of the last 2000 years.”

Jin *et al.* (2004) analyzed percent organic carbon and Rb/Sr ratios in a sediment core extracted from the deepest part of Daihai Lake (112°32′–112°48′E, 40°28′–40°39′N) in Inner Mongolia, which they describe as being located “in the transitional zone between semi-arid and semi-humid conditions that is sensitive to East Asian monsoon variability.” They found the data they obtained “support two distinct Little Ice Age cooling events centered at ~850 yr BP and ~150 yr BP,” as well as “the Medieval Warm Period between 1200 and 900 yr BP,” which they say “was warmer than the present, with higher chemical weathering than at present,” citing Jin *et al.* (2002). Such findings echo the results of Zhangdong *et al.* (2002), who also used rubidium/strontium ratio, calcium carbonate, and organic concentration data of sediments cored from Daihai Lake (112°38′E, 40°33′N) to reconstruct the climate of that region over the past 2,200 years. Their results indicate the existence of a “warm and humid” climate that defined

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the Medieval Warm Period between AD 800 and 1100, which also exhibited the “strongest chemical weathering during the last 2,200 years.”

Qiang *et al.* (2005) conducted stable carbon isotope analyses conducted on sediment cores taken from Lake Sugan (38°51.19'N, 93°54.09'E), located in the northeastern region of the Tibetan Plateau, to produce a proxy of winter temperatures over the past 2,000 years. The results indicate a warm and dry period between 580 and 1200 AD, which they state “corresponds to the Medieval Warm Period.” The author’s Figure 3 reveals the MWP was probably at least as warm between ~AD 1100 and 1200 as it is today.

Chen *et al.* (2009) studied varved sediments retrieved from cores extracted from Lake Sugan to develop a 1,000-year high-resolution (~10 years) salinity history of the lake, based on the relative abundances of chironomid species they identified via microscopic examination of head capsules found in the sediments. This work suggested, they write, “over the last millennium, the Sugan Lake catchment has alternated between contrasting climatic conditions, having a dry climate during the period AD 990–1550, a relative humid climate during the Little Ice Age (AD 1550–1840), and a dry climate again from AD 1840 onwards.” They associate the first of the three periods with “the Medieval Warm Period in China,” which they describe as being “warm and dry.”

Li *et al.* (2006) conducted a variety of proxy analyses, including palynology, microfossil charcoal, stable isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), and sediment geochemistry, on a 3.6-m sediment core taken from a relict oxbow lake in the Western Liaohe River Basin (42.07°N, 119.92°E) of northeastern China to reconstruct the environmental history of that region over the past 5,400 years. The results indicate the existence of a period of enhanced warmth and wetness from about AD 800 to 1400, which the researchers associate with the Medieval Warm Period.

Liu *et al.* (2006b) used three well-dated *Sabina Przewalskii* ring-width chronologies derived from 77 trees growing in three locations near Dulan, China on the northeastern Tibetan Plateau (36.0–36.3°N, 98.2–98.6°E) to reconstruct annual precipitation variations in that region over the period AD 850–2002. They compared their results with instrumental temperature data for that region at that time..

Working with 10-year moving averages, the 13 scientists found precipitation and temperature were “significantly correlated with $r = 0.85$ ($p < 0.0001$), after the precipitation lagged temperature for 2

years.” They produced a 40-year moving average curve that was “significantly correlated with seven temperature curves of the Northern Hemisphere,” which led them to conclude their 40-year smoothed reconstruction “could be regarded as the millenary temperature curve for the northeastern Tibetan Plateau.”

Liu, *et al.*’s “millenary temperature curve” clearly shows the 40-year-averaged temperature proxies in the vicinity of AD 915 are greater than those at the end of the twentieth century, which comprise the next highest peak of the record. Thus this study documents another specific instance where peak temperatures of the Medieval Warm Period likely were greater than peak temperatures of the twentieth century.

Jin *et al.* (2007) studied “the evolutionary history of permafrost in the central and eastern Qinghai-Tibetan Plateau since the end of the late Pleistocene, using relict permafrost and periglacial phenomena along the Qinghai-Tibet Highway from Gomud to Lhasa, the Qinghai-Kang (western Sichuan) Highway from Xi’ning to Yusu, adjacent areas, and the Xinjiang-Tibet Highway from Yecheng to Lhasa.” They described permafrost and deduced environmental conditions during “the Megathermal period in the middle Holocene (~8500–7000 to ~4000–3000 years BP)” as well as “the warm period in the later Holocene (1000 to 500 years BP).” In comparing environmental and permafrost characteristics of those periods of elevated warmth with those of the present, the three researchers from the Chinese Academy of Sciences report “the total areas of permafrost [during the Megathermal period of the middle Holocene] were about 40–50% of those at present,” while “mean annual air temperatures were ~2–3°C higher.” Moreover, during the warm period of the late Holocene “the retreating of permafrost resulted in a total permafrost area of ~20–30% less than at present,” and mean annual air temperatures were “1.5–2.0°C warmer than at present.”

Liu *et al.* (2007) reconstructed a 1,000-year temperature history of the middle Qilian Mountains of China (37–39°N, ~99–103°E) at the convergence of the Qinghai-Xizang Plateau, the Inner Mongolia-Xinjiang Plateau, and the Loess Plateau, working with ring-width and $\delta^{13}\text{C}$ data derived from long-lived Qilian juniper (*Sabina przewalskii* Kom.) trees. Their reconstruction captured about 75 percent of the temperature variance over the calibration period 1960–2000 and correlated well with the Northern Hemisphere temperature reconstruction of Esper *et al.* (2002). As the six scientists describe it, the two sets

of reconstructed temperature data (theirs and that of Esper *et al.*) “reveal that the Medieval Warm Period and Little Ice Age were synchronous in China and the Northern Hemisphere.” In addition, they note the two warmest intervals in their temperature reconstruction were 1060–1150 and 1900–2000, with corresponding peaks occurring around 1100 and 1999 that are essentially identical. Their results do not extend as far back in time as those of Esper *et al.*, which rise to their highest level before Liu *et al.*’s history begins. Liu *et al.* acknowledge their reconstructed temperature history “has not included all of the Medieval Warm Period and, perhaps, not even its warmest period.”

Ge *et al.* (2007) reviewed proxy temperature records of China that spanned the entire Holocene, focusing on the last two millennia, noting it is widely believed “increasing concentrations of greenhouse gases in the atmosphere are causing higher global atmospheric temperatures” and, therefore, “paleoclimate data are essential for both checking the predictions of climate models and characterizing the natural variability of [Earth’s] climate system.”

They found the warmest period of the Holocene occurred between 9,600 and 6,200 years ago, during portions of which temperatures “were about 1°C–5°C higher than the present in China.” They also report “during the past two millennia, a warming trend in the 20th century was clearly detected, but the warming magnitude was smaller than the maximum level of the Medieval Warm Period,” which they describe as having occurred between AD 900 and 1300. They state, “the Current Warm Period has lasted [only] 20 years from 1987 to 2006,” and the annual mean temperature series of China since AD 1880 indicates the country was warmer in the mid-1940s than at the time of their study.

Tan *et al.* (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau’s northeast margin since AD 960 based on an analysis of Chinese historical records. They compared the result with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories. This work revealed, “high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere.” They used their precipitation record to infer a Medieval Warm Period that stretched from about AD 960 to 1230, with temperature peaks in the vicinity of AD 1000 and 1215 that clearly exceeded the twentieth century peak temperature of

the Current Warm Period. They also found “good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record.” These findings harmonize, they write, with “numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene,” in support of which they attached 22 scientific references. The four scientists conclude the “synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity,” which apparently produced a Medieval Warm Period both longer and stronger than what has been experienced to date during the Current Warm Period in the northeast margin of the Tibetan Plateau.

Zhang *et al.* (2008) studied a stalagmite found in China’s Wanxiang Cave (33°19’N, 105°00’E), which they say is located on the fringes of the area currently affected by the Asian Monsoon and is thus sensitive to (and integrates broad changes in) that annually recurring phenomenon. The 17 researchers developed a $\delta^{18}\text{O}$ record with an average resolution of 2.5 years that “largely anti-correlates with precipitation” and runs continuously from AD 190 to 2003. Zhang *et al.* demonstrate the record “exhibits a series of centennial to multi-centennial fluctuations broadly similar to those documented in Northern Hemisphere temperature reconstructions, including the Current Warm Period, Little Ice Age, Medieval Warm Period and Dark Age Cold Period.” When one compares the peak warmth implied by their data for the Current and Medieval Warm Periods, it is easy to see the Medieval Warm Period was the warmer of the two.

Zhang *et al.* superimposed their $\delta^{18}\text{O}$ record upon individual plots of Northern Hemispheric temperature as derived by Esper *et al.* (2002), Moberg *et al.* (2003), and Mann and Jones (2003). In the first of these comparisons, the two records were closely matched, both indicating greater peak warmth during the Medieval Warm Period than during the Current Warm Period. The same was true of the second comparison, and in the third comparison the records also were closely matched over the majority of their expanse. Over the last decades of the twentieth century, however, the temperatures of the Mann and Jones record rise far above the temperatures implied by the Zhang *et al.* record (and, therefore, those of the Esper *et al.* and Moberg *et al.* records as well), suggesting this anomalous behavior of the Mann and Jones record is the result of a defect not found in the

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other three datasets. That defect is likely Mann and Jones' use of directly measured as opposed to reconstructed temperatures over their record's last few decades, which leads to their anomalous end-point "oranges" not telling the same story as told by everyone else's "apples."

It is also interesting to note the Zhang *et al.* record "correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes." Since none of the last four phenomena can influence the first, it stands to reason solar variability is likely what has driven the variations in the other factors. In a commentary accompanying Zhang *et al.*'s article, Kerr (2008) notes the Zhang *et al.* record had been described by other researchers as "amazing," "fabulous," and "phenomenal," and it "provides the strongest evidence yet for a link among sun, climate, and culture." In addition, it provides equally strong evidence for at least the Northern-Hemispheric extent of the Medieval Warm Period and its greater and more persistent warmth than that of the Current Warm Period.

Based on a study of historical documents covering the period AD 1000–1950 and instrumental data from meteorological stations for the period 1950–2003, Zhang *et al.* (2008) developed a millennial-scale temperature index for the Yangtze Delta region of China that revealed "three distinct climate periods": the "Warm Medieval Period (AD 1000–1400), Little Ice Age (AD 1400–1920), and the ongoing well-established Global Warming Period (AD 1920–present)." This record documents a continuous period from about AD 1200 to 1235 when it was significantly warmer than the peak warmth recorded during the "well-established Global Warming Period." Similar results were found previously by Yi *et al.* (2006), who analyzed arboreal pollen, non-arboreal pollen, and spores contained in a sediment core retrieved from the Changjiang prodelta (31°01.1'N, 122°47.0'E). This effort revealed, they write, "relatively warm/wet conditions comparable to [the] Medieval Warm Period (AD 910–1085) with a strengthen[ed] summer monsoon." Based on the findings of others, Yi *et al.* further state, "the mean temperature during this period was 1–2°C warmer than that of today."

Xiao *et al.* (2012) analyzed pollen, charcoal, and magnetic susceptibility data from a 150-cm-long sediment core extracted from the central portion of northern Taibai Lake (29°59'43"N, 115°48'27"E) in the middle reach of the Yangtze River. They

concluded "vegetation changes [over the time interval AD 1050–1320] were mainly controlled by climatic changes, with limited influence from human activity," and this period was "more warm and humid" than those that preceded and followed it. They say these observations mean "the 'Medieval Warm Period' occurred in the middle reach of the Yangtze River," further noting "the reconstructed results of Ge *et al.* (2003, 2004) and the simulated results of Liu *et al.* (2005) also verified its existence in eastern China and even the whole of China."

Ma *et al.* (2008) analyzed multi-proxy data, including "¹⁴C, grain size, microfossil, plant seeds, and geochemical elements," obtained from sediment retrieved from excavations made in the dry lake bed of Lop Nur China's West Lake (40°27'129" N, 90°20'083" E) in order "to amply discuss," as they describe it, "the climate and environment changes during the MWP," which they identify as occurring between AD 900 and 1300. They found the "sedimentary environment was stable around the MWP, with weak storm effect" and "the upper and lower sediments showed frequent strong storm effect." They also report "microfossils and plant seeds were abundant in this stage [MWP], which indicated a warm and humid fresh or brackish lake environment." Thereafter, "in the late period [AD 1300 to 1650], the environment turned worse, storm effect was intensified ... and the climate began to dry, leading to shriveling and death of many plants such as red willows." Ma *et al.* conclude "the environment was the best" over the period AD 1100 to 1300, stating, "temperature was almost the same [as] or a little higher than nowadays," providing another example of the widespread occurrence of the Medieval Warm Period, which they describe as "one of the most significant climate episodes in the world."

Yang *et al.* (2009) synthesized proxy records of temperature and precipitation in arid central Asia over the past two thousand years, focusing on the relationship between temperature and precipitation on timescales ranging from annual to centennial (Figure 4.2.4.4.1.4). With respect to temperature, they report "the most striking features are the existence of the Medieval Warm Period (MWP) and the Little Ice Age (LIA)," as well as the earlier Roman Warm Period (RWP) and Dark Ages Cold Period (DACP), plus what they call "a recent warming into the 20th century" they identify as the Current Warm Period (CWP). As for precipitation, the five researchers state the MWP "corresponded to an anomalously dry period whereas the cold LIA coincided with an

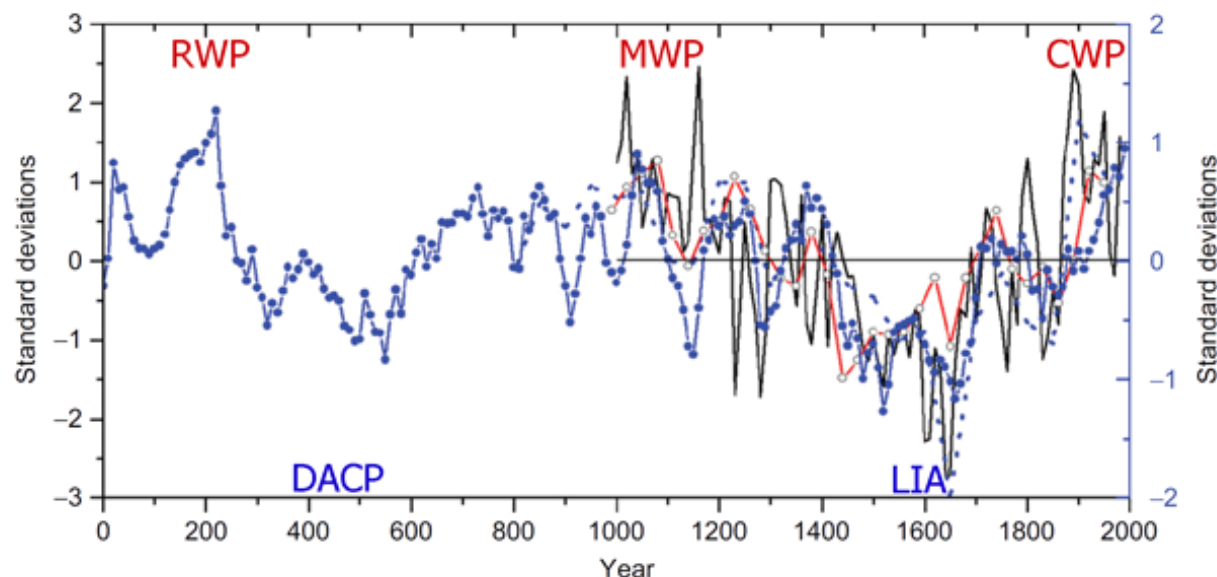


Figure 4.2.4.1.4. Standardized representations of various reconstructions of the temperature history of arid central Asia. Adapted from Yang, B., Wang, J., Brauning, A., Dong, Z., and Esper, J. 2009. Late Holocene climatic and environmental changes in arid central Asia. *Quaternary International* **194**: 68–78.

extremely wet condition.” Once again, a substantive body of evidence is presented for the natural, non- CO_2 -induced, millennial cycling of climate that has alternately brought the world into and then out of the Roman Warm Period, the Dark Ages Cold Period, the Medieval Warm Period, and the Little Ice Age, providing good reason to conclude the continuation of that cycle has likely brought the planet into the Current Warm Period and will ultimately bring the world out of its latest extended “heat wave.”

Hong *et al.* (2009) write of the Medieval Warm Period, “because it is a distinct warm period nearest to the modern warming period and happened before the Industrial Revolution, it naturally becomes a [source of] comparison with modern warming.” They add, “a universal concern in academic circles is [1] whether it also existed outside the European region and [2] whether it is a common phenomenon.” In a study designed to broach both questions, they extracted cores of peat from a location close to Hani Village, Liuhe County, Jilin Province, China ($42^\circ 13' \text{N}$, $126^\circ 31' \text{E}$) and used them to develop “a peat cellulose $\delta^{18}\text{O}$ temperature proxy record proximately existing for 14,000 years.”

These efforts revealed the existence of the MWP on the Chinese mainland over the period AD 700–1400, peaking at about AD 900. The eight researchers report phenological data from east China (Ge *et al.*,

2006) and tree-ring records from west China (Yang *et al.*, 2000) also indicate “the temperature on the Chinese mainland was distinctly warmer during the MWP.” They say MWP temperatures were as much as “ $0.9\text{--}1.0^\circ\text{C}$ higher than modern temperatures (Zhang, 1994).”

Hong *et al.* further note, “sudden cooling events, such as the Older Dryas, Inter-Allerod, Younger Dryas, and nine ice-rafted debris events of the North Atlantic,” described by Stuiver *et al.* (1995) and Bond *et al.* (1997, 2001), “are almost entirely reiterated in the temperature signals of Hani peat cellulose $\delta^{18}\text{O}$.” And “these cooling events show that the repeatedly occurring temperature cooling [and warming] pattern not only appeared in the North Atlantic Region in the high latitudes, but also in the Northwest Pacific Region in the middle latitudes,” indicating the recurring warming and cooling occurred “outside the European region” and was “a common phenomenon.”

Hong *et al.* also note the earlier paper of Hong *et al.* (2000), which describes a 6,000-year peat cellulose $\delta^{18}\text{O}$ record derived from nearby Jinchuan Town, Huinan County, Jilin Province, China ($42^\circ 20' \text{N}$, $126^\circ 22' \text{E}$), identified $\delta^{18}\text{O}$ periodicities of 86, 93, 101, 110, 127, 132, 140, 155, 207, 245, 311, 590, 820 and 1,046 years, which they say “are similar to those detected in solar excursions” and which they consider “further evidence for a close relationship

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between solar activity and climate variations on timescales of decades to centuries.”

The findings of Hong *et al.* (2000) were highly praised by Fairbridge (2001), who notes “almost identical equivalents are seen in solar emission periodicities and their harmonics, e.g., 86.884 years = 40 x 2.172 year Quasi Biennial Oscillation (QBO) as well as in the lunar tidal/apsides beat frequency (17.3769 years) which also matches closely with most of the longer spectral peaks, e.g., 140 (139) years, 207 (208.5), 311 (312.8), 590 (590.8) and 1046 (1042.6) years.” For these spectacular spectral findings, Fairbridge writes, “Hong *et al.* deserve the appreciation of the entire Holocene community.” And the case for a global and solar-induced Medieval Warm Period grows ever stronger, as it also does for the similar warm periods that preceded it in the prior 13,000 years, making the case for a similar origin for the Current Warm Period increasingly likely as well.

Liu *et al.* (2009) obtained a mean annual temperature history of the mid-eastern Tibetan Plateau based on Qilian juniper (*Sabina przewalskii*) tree-ring width chronologies obtained from living trees and archaeological wood for the 2,485-year period 484 BC–AD 2000, which data were calibrated against measured air temperatures for the period AD 1958–2000. They demonstrate their work to be well correlated with several temperature histories of the Northern Hemisphere. The eight researchers found four periods with average temperatures similar to “or even higher than” the mean of AD 1970–2000, beginning with the warm period of AD 401–413, which they say “was the warmest period within the last 2.5 thousand years.” They also note an archaeological documentary record from Loulan in Xinjiang province shows pomegranate was employed as currency during the Eastern Jin Dynasty (AD 317–589), because the appearance of pomegranate during that period “suggests that the temperature at that time was higher than nowadays,” citing Zhang and Zhang (2006). In addition, they note the rate of warming that led to the early ultra-warm period of their record was “unprecedented in the last 2500 years.” And the last of the four ultra-warm periods was also slightly warmer than it was at the end of the twentieth century.

Liu *et al.* also suggest the high-temperature intervals of the AD 400–1000 period were relatively good times, as the downfalls of most of the major dynasties in China coincided with intervals of low temperature, citing the demise of the Qin, Three Kingdoms, Tang, Song (North and South), Yuan,

Ming, and Qing Dynasties.

Chen *et al.* (2009) studied a sediment core taken from a mountain lake (Duck Pond, 25°10.441'N, 121°33.013'E) in Northern Taiwan that “represents deposition from AD 650 to present.” They identified, measured, and analyzed “pollen, spores, diatoms, organic carbon, nitrogen, and $\delta^{13}\text{C}$ of organic matter in lake sediments to infer climate changes and reconstruct the paleo-environment of subtropical Taiwan over the past ~1300 years,” temporally delineating five climate zones in the process. Zone III (AD 1050–1250) was “wet and warmer; ~MWP [Medieval Warm Period],” Zone IV (AD 1250–1790) was “wetter and colder than in Zone III; corresponding to LIA [Little Ice Age],” and Zone V (AD 1790–2000) was “drier and warmer than in Zone IV.” They state, “in Europe and other regions, there was a short warm period (the medieval warm period, or MWP) prior to the LIA,” and their “Zones III and IV likely correspond to such warm and cold periods.” They also found the ratio of arboreal pollen (AP) to non-arboreal pollen (NAP) “showed a positive correlation with temperature” They report the peak AP/NAP ratio of the MWP was about three times greater than the peak AP/NAP ratio of the CWP, suggesting the peak warmth of the former period must have been considerably greater than the peak warmth of the latter period.

Wang *et al.* (2011) analyzed pollen data obtained from ten lake sediment cores and two land cores to assess the species abundances and alterations of forest-covered areas in northern Taiwan (23°17'N–25°18'N, 120°54'E–122°02'E) in response to changes in humidity and temperature over the past 2,000 years. The researchers found the climate of northern Taiwan was “wet and warm during 1000–500 cal. yr BP, which corresponded to the Medieval Warm Period (MWP).” They also note “an increased density and dispersal of *Tsuga* pollen corresponding to 500–200 cal. yr BP was observed, which corresponded to the Little Ice Age (LIA).” The authors’ Figure 6, which presents a relationship between *Tsuga* pollen and temperature, shows the MWP was slightly warmer than the CWP.

Ge *et al.* (2010) write, “knowledge of past climate can improve our understanding of natural climate variability and also help address the question of whether modern climate change is unprecedented in a long-term context.” They report “regional proxy temperature series with lengths of 500–2000 years from China have been reconstructed using tree rings with 1–3 year temporal resolution, annually resolved

stalagmites, decadal resolved ice-core information, historical documents with temporal resolution of 10–30 years, and lake sediments resolving decadal to century time scales,” noting “these proxies provide quantitative estimates of past climate through statistical calibration against instrumental temperature measurements.”

Ge *et al.* divided China into five regions for their analysis and developed temperature reconstructions for each: three composite temperature reconstructions that extended back in time a full two millennia (Northeast, Tibet, Central East), one that extended back approximately 950 years (Northwest), and one that went back only about 550 years (Southeast). In the Northeast, the six scientists found a warm period “between approximately 1100 and 1200 that exceeded the warm level of the last decades of the 20th century.” In Tibet, there was a “warming period of twenty decadal time steps between the 600s and 800s” that was “comparable to the late 20th century.” In the Central East, there were two warm peaks (1080s–1100s and 1230s–1250s) with “comparable high temperatures to the last decades of the 20th century,” although the graph of their data indicates these two periods were warmer than the last decades of the twentieth century. And in the Northwest, “comparable warm conditions in the late 20th century are also found around the decade 1100s.”

Gen *et al.*’s work clearly shows there is nothing unusual, unnatural, or unprecedented about the country’s current level of warmth. Thus there is no compelling reason to attribute late twentieth century warmth in China to twentieth century increases in the atmospheric concentrations of CO₂ or any other greenhouse gases.

Shi *et al.* (2010) extracted 67 cores from 29 healthy trees in an old-growth forest in Nangcai, Zaduo County, at a site (32°39′36″N, 95°43′14″E) undisturbed by human activities. They developed a ring-width history covering the period AD 1360–2005 based on what they considered to be the best 46 cores from 23 trees. For the period AD 1961–2005, they derived a relationship between annual tree-ring width and directly measured May–June mean maximum air temperature, which they used to reconstruct a similar temperature history for the entire 645-year period. Based on an 11-year moving average of these results, they identified a 17-year warm period (AD 1438–1455), which occurred in the latter stages of the global MWP. As best as can be determined from the graphs of their results, this period was about 1.2°C warmer than the last decade of their temperature

history (AD 1995–2005).

Li *et al.* (2010) developed a composite temperature history of the Hetao region of China stretching 5,000 years back in time from the early 2000s, based on pollen data from Daihai Lake (40°N, 112°E), oxygen isotope data from a salt lake in Yikezhaomeng, Inner Mongolia (39°N, 109°E), and total organic carbon data from Jingbian County (37°N, 108°E). This temperature history revealed “the climate was relatively warm” between 1450 and 1,000 calendar years before present (AD 550–1000), which “corresponded to the Medieval Warm Period.” It is clear from their graph of the data that the peak warmth of the MWP was greater than the peak warmth of the CWP.

Zhou (2011), a scientist with the State Key Laboratory of Severe Weather of the Chinese Academy of Meteorological Sciences in Beijing, wrote in an introductory editorial in a special issue of the *Chinese Science Bulletin* (October 2011), “research on global climate change has been at the frontier of the contemporary sciences” and “debate has focused on whether the greenhouse effect produced by human activities is a major factor responsible for modern climate warming.”

Zhou reports “in 2009, the major project ‘Research on tree-ring and millennium climate change in China’ was implemented under the support of the National Natural Science Foundation of China.” Noting eight articles published in this special issue of the *Bulletin* “present partly preliminary results obtained by the project over the past two years,” he summarizes their findings: The eight articles “reveal some characteristics and regularities of changes in temperature and precipitation in China and in East Asian monsoons over the past 1000 years” that qualify as “notable conclusions,” of which he lists only two. But those two are extremely important: (1) “temperatures in the Medieval Warm Period are comparable to those in the current warm period over China,” and (2) “the effect of solar activity on climate cannot be neglected in any period of the millennium.”

Tian *et al.* (2011) reconstructed a 1,910-year-long time series—stretching from AD 2 to AD 1911—of outbreaks of Oriental migratory locusts in China, based on information the researchers extracted from more than 8,000 historical documents and relationships they developed between these data and indices of temperature at annual and decadal time scales. They found “a negative association between locust abundance and annual temperature,” which was most strongly manifest when the temperature index was

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representative of the whole of China. As Figure 4.2.4.4.1.5 shows, the interval of lowest locust index during this period (~AD 1030–1250)—which would thus represent the warmest period of the record—falls right in the middle of the mean global Medieval Warm Period.

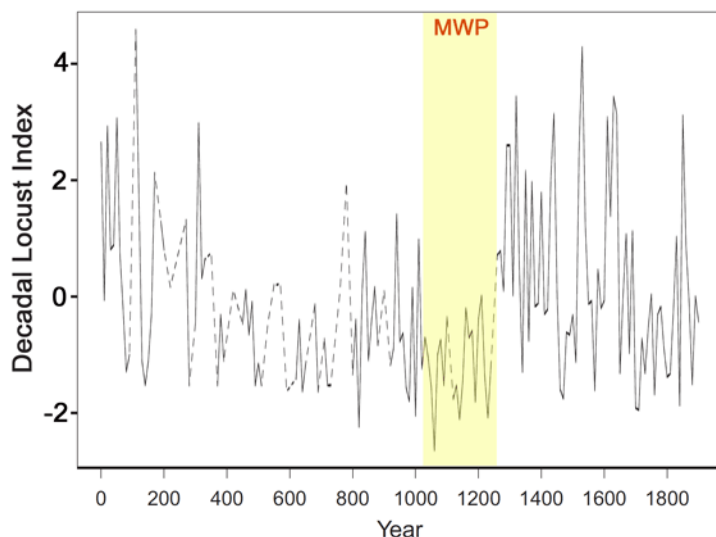


Figure 4.2.4.4.1.5. Chinese decadal locust abundance index vs. year. Dashed lines connect data points across periods with no locust reports. Adapted from Tian, H., Stige, L.C., Cazelles, B., Kausrud, K.L., Svarverud, R., Stenseth, N.C., and Zhang, Z. 2011. Reconstruction of a 1,910-y-long locust series reveals consistent associations with climate fluctuations in China. *Proceedings of the National Academy of Sciences USA* **108**: 14,521–14,526.

Wang *et al.* (2012) note “lakes are excellent sensors of environmental change” and “lake sediments can provide well-resolved records of change on different time scales.” They also note “crater and maar lakes are especially sensitive to climate change because typically they have a small catchment area and limited inflow/outflow.” Moreover, such lakes “often provide high-resolution records due to limnological processes favorable to the development and preservation of seasonally laminated sediments,” citing Zolitschka *et al.* (2000). They add, “diatoms are excellent indicators of environmental conditions and have been widely used to reconstruct Holocene climate variability,” citing Smol and Cumming (2000), Battarbee *et al.* (2001), and Mackay *et al.* (2003).

Wang *et al.* retrieved a 66.5-cm-long sediment core from Lake Erlongwan, one of eight maar lakes in the Long Gang Volcanic Field of Jilin Province, NE

China (42°18'N, 126°21'E), which they describe as a closed dimictic lake that occupies an area of 0.3 km² and has a small catchment (0.4 km²) with no natural inflows or outflow. They dated the sediment using radiometric ²¹⁰Pb, ¹³⁷Cs and ¹⁴C analyses and analyzed it for diatom species and quantities. Although they note diatoms “are generally not known to be very sensitive to water temperature,” they state, “climate affects the physical properties of the lake water column, especially as it controls the seasonal durations of ice cover, water column mixing and stratification, which all have profound effects on the availability of nutrients and light necessary for algal photosynthesis and growth.” Thus “climate has an indirect influence on the composition and productivity of phytoplankton, especially non-motile organisms such as diatoms.”

The ten researchers made “a detailed qualitative paleolimnological interpretation of the Lake Erlongwan sediment sequence based mainly on the growing body of literature that focuses on the ecology of planktonic diatoms, especially their responses to climate-driven changes in limnology.” They report “three intervals were identified by their diatom assemblages and correspond within dating uncertainties to the Medieval Warm Period, the Little Ice Age and the 20th century warming trend.” During the MWP, “the duration of the summer was longer while the spring and autumn were shorter than the 20th century.”

And they state “the period between ca. AD 1150 and 1200 was the warmest interval of the past 1000 years.”

He *et al.* (2013) extracted sediment cores from the center of Lake Gahai (37°08'N, 97°31'E) and Lake Sugan (38°52'N, 93°75'E) and developed a decadal resolved alkenone-based temperature record for that part of the Qaidam Basin of the northern Tibetan Plateau that covered the last 2,600 and 2,200 years, respectively. Both records revealed the presence of the MWP between AD 700 and 1350. The ten Chinese researchers report regional temperatures during the peak warmth of the MWP, which occurred over the period AD 1100–1200 in Lake Gahai (see Figure 4.2.4.4.1.6) and AD 1000–1100 in Lake Sugan (see Figure 4.2.4.4.1.7), exceeded those in the recent warm period by approximately 1.9 and 4.0 °C, respectively.

The studies reviewed in this section make it clear that for a considerable amount of time during the Medieval Warm Period, most if not all of China exhibited warmer conditions than those of modern times. Those earlier high temperatures were caused by something other than elevated atmospheric CO₂ concentrations, and whatever was responsible for them also could be responsible for today's warmth. A growing body of evidence speaks to the reality of a global millennial-scale oscillation of climate totally independent of the air's CO₂ concentration. There is every reason to believe the most recent warming phase of this cycle, which ended the Little Ice Age and launched the Current Warm Period, was entirely natural and not the result of the coincidental increase in the air's CO₂ content.

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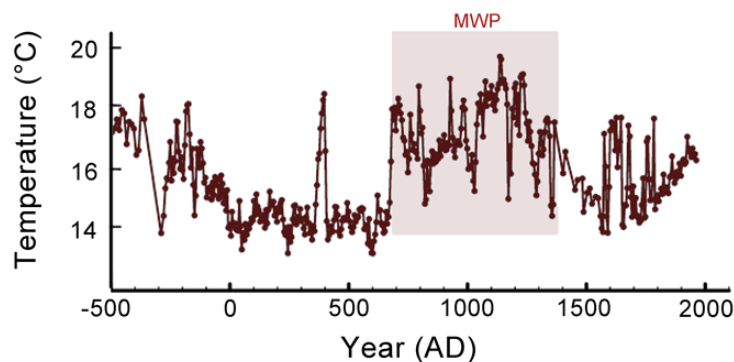


Figure 4.2.4.4.1.6. Alkenone-based temperature proxy from Lake Gahai. Adapted from He, Y.-X., Liu, W.-G., Zhao, C., Wang, Z., Wang, H.-Y., Liu, Y., Qin, X.-Y., Hu, Q.-H., An, Z.-S., and Liu, Z.-H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

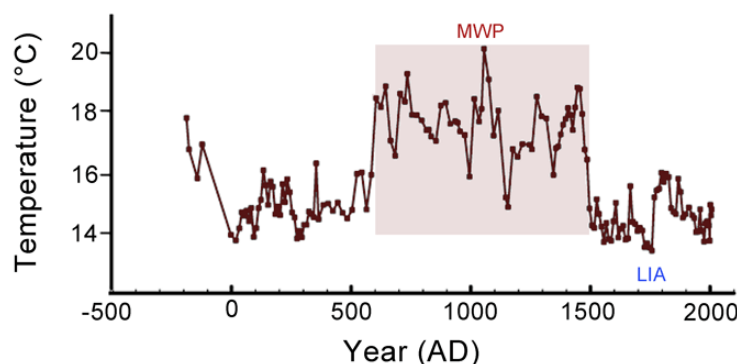


Figure 4.2.4.4.1.7. Alkenone-based temperature proxy from Lake Sugan. Adapted from He *et al.* (2013).

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4.2.4.4.2 Japan

The Medieval Warm Period (MWP) was a global climate anomaly that encompassed a few centuries on either side of AD 1000, when temperatures in many parts of the world were even warmer than they are currently. The degree of warmth and associated changes in precipitation varied from region to region, and the MWP was expressed somewhat differently in different parts of the world. How it manifested itself

in Japan is the subject of this subsection.

Kitagawa and Matsumoto (1995) analyzed $\delta^{13}\text{C}$ variations of Japanese cedars growing on Yakushima Island, southern Japan (30°20'N, 130°30'E) to reconstruct a high-resolution proxy temperature record covering the past two thousand years. They applied spectral analysis to the $\delta^{13}\text{C}$ time series to determine if any significant periodicities were present in the data. They found significant decadal to centennial-scale variability throughout the record, with temperatures fluctuating by about 5°C across the series (see Figure 4.2.4.4.2.1). Most notable among the fluctuations were multi-century warm and cold epochs. Between AD 700 and 1200, for example, there was about a 1°C rise in average temperature, which “appears to be related to the ‘Medieval Warm Period.’” In contrast, they found temperatures were about 2°C below the long-term pre-1850 average during the multi-century Little Ice Age that occurred between AD 1580 and 1700.

Kitagawa and Matsumoto also report finding significant temperature periodicities of 187, 89, 70, 55, and 44 years. Noting the 187-year cycle closely corresponds to the well-known Suess cycle of solar activity, and the 89-year cycle compares well with the Gleissberg solar cycle, they conclude their findings provide strong support for a Sun-climate relationship. Their findings also support the growing body of evidence indicating the Medieval Warm Period and Little Ice Age were global phenomena. They thus conclude there was nothing unusual, unnatural, or unprecedented about Current Warm Period temperatures in this region, which remain about one degree Celsius lower than the peak warmth of the Medieval Warm Period.

Noting instrumental climate records are insufficient to be used alone in understanding natural climate variability, Adhikari and Kumon (2001) analyzed the total organic carbon, total nitrogen, and sand content of sediment cores extracted from Lake Nakatsuna in central Japan (36°30'N, 137°51'E) to produce a proxy record of climate for this region that covered the past 1,300 years. This project revealed both the Medieval Warm Period (AD 900–1200), which the two researchers said was “warmer than any other period during the last 1300 years,” and the Little Ice Age (AD 1200–1950), which was punctuated by three major cold phases (AD 1300–1470, 1700–1760 and 1850–1950). Their work thereby provides more evidence for a global Medieval Warm Period and a global Little Ice Age and suggests the Intergovernmental Panel on Climate Change (IPCC)

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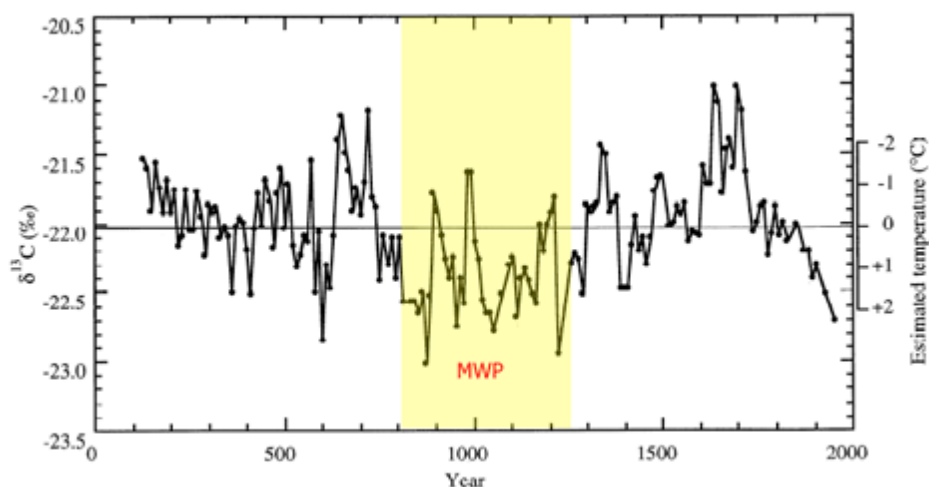


Figure 4.2.4.4.2.1. Proxy temperature record obtained from a $\delta^{13}\text{C}$ record of a giant Japanese cedar tree on Yakushima Island. Adapted from Kitagawa, H. and Matsumoto, E. 1995. Climatic implications of $\delta^{13}\text{C}$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.

should never have abandoned its original climate history of the world—which more accurately depicted these significant temperature excursions (Houghton *et al.*, 1990)—in favor of the flawed “hockey stick” temperature history of Mann *et al.* (1998, 1999).

Daimaru *et al.* (2002) write, “in snowpatch grasslands, plant distributions follow the contours of the snowmelt gradient around summer snowpatches,” producing “similarly steep gradients in plant productivity and topsoil (e.g. Billings and Bliss, 1959; Helm, 1982; Kudo, 1991; Stanton *et al.*, 1994.)” They state, “in the subalpine zone of northeastern Japan, sites where the snow cover disappears after July are usually occupied by ‘snowpatch bare grounds’ with extremely poor vegetation cover” that is “encircled by snowpatch grassland,” citing Yamanaka (1979). As a result, “litter fall and the organic content in topsoil decrease toward the center of a snowpatch because the period for plant growth becomes shorter with delay in the time of snow disappearance,” so in current “snowpatch grass-lands, peaty topsoil is restricted to sites where snowmelt comes early.” The unique situation provided by a snowpatch can provide a good opportunity for paleoclimatic reconstructions based on vertical profiles of soil characteristics at various locations along transects moving outwards from summer snowpatches.

Daimaru *et al.* dug 27 soil pits at various locations in and around the center of a snowpatch grassland within a shallow depression of landslide origin on the southeastern slope of Japan’s Mt.

Zarumori (~39.8°N, 140.8°E), determining its age based on ^{14}C dating and tephrochronology. They state, “peaty topsoils were recognized at seven soil pits in the dense grassland, whereas sparse grassland lacked peaty topsoil.” They also note, “most of the buried peat layers contained a white pumice layer named ‘To-a’ that fell in AD 915.” This observation and the ^{14}C dating led them to conclude the buried peat layers in the poor vegetation area indicate “warming in the melt season” as well as “a possible weakened winter monsoon in the Medieval Warm Period,” which their

data suggest prevailed at the site throughout the tenth century; i.e., AD 900–1000. They observe “many studies have reported climatic signals that are correlated with the Medieval Warm Period from the 9th to 15th centuries in Japan,” suggesting the possibly weakened winter monsoon of AD 900–1000 may have been a consequence of the warmer temperatures of that period.

Kitagawa *et al.* (2004) analyzed pollen in a sediment core retrieved from Karikomi Lake in the border area between the Hida and Echizen regions of Japan in the Hakusan mountains, as well as numerous local histories. They described the historical development of a practice called *hansaibai*, whereby local inhabitants encouraged the growth of horse-chestnut (*Aesculus turbinata*) trees as a food source during cold-induced famines of the Little Ice Age. Prior to that time, when the Medieval Warm Period prevailed, the mix of tree species in the local forest was that of “a warm temperate forest,” they found. At about AD 1360, however, the warm-climate species “decreased, suggesting cooler climatic conditions,” corresponding to “the beginning of the Little Ice Age as generally recognized in Japan (Sakaguchi, 1995).”

During this multi-century cold spell, Kitagawa *et al.* report “serious famines frequently occurred because of adverse climatic conditions,” three of which were especially serious: “both the Kyoho famine in 1732 and the Tenmei famine (1782–1787) resulted in population decreases of about one million, and during the Tenpo famine (1823–1839) the

population declined by ca. 290,000 (Nakajima, 1976)."

These observations clearly reveal the existence of both the Medieval Warm Period and Little Ice Age in Japan, strengthening the proposition that these distinctive climatic intervals were in fact global as opposed to merely regional phenomena restricted to countries bordering the North Atlantic Ocean. They also reveal the harshness of the Little Ice Age, which the five Japanese scientists say "caused serious famines in Europe, Argentina, and Mexico (Appleby, 1980; Cioccale, 1999; Post, 1984; Swan, 1981)," the latter two of which locations are also far removed from the North Atlantic Ocean.

Goto *et al.* (2005) reconstructed the ground surface temperature history from a borehole off the southern coast of Lake Biwa, the largest and oldest lake in Japan, to produce a proxy climate record spanning the past 3,000 years. The Medieval Warm Period was described as a period of warmth from the eighth to the twelfth century A.D. A comparison between the Medieval and Current Warm Periods could not be made because of anthropogenic and environmental factors influencing the record.

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 "spectral analysis for SST variation revealed a statistically significant peak with 1470-year periodicity." 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.

Yamada *et al.* (2010) analyzed sediment cores they obtained in July 2007 from Lakes Ni-no-Megata (39°57'N, 139°43'E) and San-no-Megata (39°56'N, 139°42'E) on the Oga Peninsula of northeastern Japan, measuring a variety of properties including sulfur content and coarse mineral grains. The former served as a proxy for paleo-Asian summer monsoon activity, and the latter provided a proxy for paleo-Asian winter monsoon activity over the last two millennia. These data reveal the presence of a

cold/dry interval from AD 1 to 750, a warm/humid interval from AD 750 to 1200, and another cold/dry interval from AD 1200 to the present. The scientists say these intervals could represent, respectively, "the Dark Ages Cold Period (DACP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA)."

They note their findings complement those of Kitagawa and Matsumoto (1995), whose study of tree-ring records in southern Japan "suggested the existence of one warm interval at AD 750–1300 and two cold intervals at AD 200–750 and AD 1600–1800," and the findings of Sakaguchi (1983), whose study of the pollen record of peaty sediments in central Japan revealed "an unusual warm interval (AD 700–1300) and a cool interval (ca. AD 250–700)." In addition, they write, the "strong summer monsoon and weak winter monsoon at Lakes Ni-no-Megata and San-no-Megata from AD 750–1200 correlates with the lower $\delta^{18}\text{O}$ values from Wangxiang Cave (Zhang *et al.*, 2008) and lower values of minerogenic clastic content (Chu *et al.*, 2009)." This is further evidence of the global scope of the millennial-scale oscillation of climate that reverberates throughout both glacial and interglacial periods.

Aono and Saito (2010) "investigated documents and diaries from the ninth to the fourteenth centuries to supplement the phenological data series of the flowering of Japanese cherry (*Prunus jamasakura*) in Kyoto, Japan, to improve and fill gaps in temperature estimates based on previously reported phenological data." They "reconstructed a nearly continuous series of March mean temperatures based on 224 years of cherry flowering data, including 51 years of previously unused data, to clarify springtime climate changes" and estimated other cherry full-flowering dates "from phenological records of other deciduous species, adding further data for six years in the tenth and eleventh centuries by using the flowering phenology of Japanese wisteria (*Wisteria floribunda*)."

The two researchers report their reconstruction "showed two warm temperature peaks of 7.6°C and 7.1°C, in the middle of the tenth century and at the beginning of the fourteenth century, respectively," and "the reconstructed tenth century temperatures [AD 900–1000] are somewhat higher than present temperatures after subtracting urban warming effects." They add, "the general pattern of change in the reconstructed temperature series in this study is similar to results reported by previous studies, suggesting a warm period in Asia corresponding to the Medieval Warm Period in Europe."

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4.2.4.4.2 Russia

Early evidence for the Medieval Warm Period in Russia was provided by Naurzbaev and Vaganov

(2000), who developed a 2,200-year proxy temperature record (212 BC to 1996 AD) using tree-ring data obtained from 118 trees near the upper timberline in Siberia. They conclude the warming experienced in the twentieth century was “not extraordinary,” and “the warming at the border of the first and second millennia was longer in time and similar in amplitude.”

Demezhko and Shchapov (2001) studied a borehole extending to more than 5 km depth, reconstructing an 80,000-year history of ground surface temperature in the Middle Urals within the western rim of the Tagil subsidence (58°24' N, 59°44'E). This history revealed a number of climatic excursions, including, they write, the “Medieval Warm Period with a culmination about 1000 years ago.” Several years later, and working along the eastern slope of the Ural Mountains (~50–58°N, ~57–62°E), Golovanova *et al.* (2012) employed temperature data obtained from 44 boreholes and calculated “the ground surface temperature at the maximum of the Medieval Warm Period in [AD] 1100–1200 was approximately the same as the present temperature.”

Hiller *et al.* (2001) analyzed subfossil wood samples from the Khibiny mountains on the Kola Peninsula of Russia (67–68°N, 33–34°E) to reconstruct that region’s climate history 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, which suggests, they write, mean summer temperatures during this “Medieval climatic optimum” were “at least 0.8°C higher than today” and “the Medieval optimum was the most pronounced warm climate phase on the Kola Peninsula during the last 1500 years.”

Hantemirov and Shiyatov (2002) examined remains of subfossil Siberian larch trees in Holocene deposits of the Yamal Peninsula over an area stretching from approximately 67°15'N to 67°40'N and from 69°50'E to 71°E, which they used to develop a 4,000-year tree-ring width chronology covering the period 2000 BC to AD 1996. Based on a transfer function that yielded mean June–July air temperatures, which they developed from temperatures measured at a meteorological station 150 km southwest of their research area over the period AD 1883–1996, the two researchers transformed their tree-ring width chronology into a June–July summer air temperature history. Hantemirov and Shiyatov write, “relatively favorable conditions existed in 1200–900 BC, 100 BC–AD 200,

and during the ‘Medieval Optimum’ (AD 700–1400),” the last of which they indicate was most pronounced over the time interval AD 1100–1350. From their Figure 11, which presents the reconstruction after applying a 20-year low-pass filter, it can be determined temperatures peaked during this interval about 0.5°C above those experienced at the end of the twentieth century.

Krenke and Chernavskaya (2002) reviewed what was known about the MWP within Russia and throughout the world based on historical, glaciological, and hydrologic evidence and dendrological, archaeological, and palynological data. They report, for example, “the northern margin of boreal forests in Canada was shifted [north] by 55 km during the MWP, and the tree line in the Rocky Mountains in the southern United States and in the Krkonose Mountains was higher by 100–200 m than that observed at the present time.”

The two members of the Russian Academy of Sciences write, “the temperature averaged over the 20th century was found to be the highest among all centennial means, although it remained within the errors of reconstructions for the early millennium.” But in reference to the “hockey stick” temperature reconstruction of Mann *et al.* (1998, 1999), they note, “one should keep in mind that the reconstructions of the early period were based nearly entirely on tree-ring data, which, because of the features of their interpretation, tend to underestimate low-frequency variations, so the temperatures of the Medieval Warm Period were possibly underestimated.” They provide further evidence for that conclusion, reporting, “the limits of cultivated land or receding glaciers have not yet exceeded the level characteristic of the early millennium.”

With respect to Russia, Krenke and Chernavskaya report large differences in several variables between the Little Ice Age (LIA) and MWP. They report, for example, an MWP to LIA drop of 1.5°C in the annual mean temperature of northern Eurasia. They also state, “the frequency of severe winters reported was increased from once in 33 years in the early period of time, which corresponds to the MWP, to once in 20 years in the LIA,” additionally noting “the abnormally severe winters [of the LIA] were associated with the spread of Arctic air masses over the entire Russian Plain.” They point out the data they used to draw these conclusions were “not used in the reconstructions performed by Mann *et al.*,” which perhaps explains why the Mann *et al.* temperature history of the past millennium does not depict the

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coolness of the LIA or the warmth of the MWP nearly as well as the more appropriately derived temperature history of Esper *et al.* (2002).

Krenke and Chernavskaya point out “an analysis of climate variations over 1000 years should help reveal natural multi-centennial variations possible at present but not detectable in available 100–200-year series of instrumental records.” Their research contradicts the claim twentieth century warming is outside the realm of natural variability and must therefore be due to anthropogenic CO₂ emissions. And in contradiction of another of Mann *et al.*’s contentions, Krenke and Chernavskaya unequivocally state “the Medieval Warm Period and the Little Ice Age existed globally.”

Esper and Schweingruber (2004) analyzed treeline dynamics over western Siberia during the twentieth century by comparing nine undisturbed polar sites located between 59° and 106°E and 61° and 72°N. They merged the information in such a way that, they write, “larger-scale patterns of treeline changes are demonstrated, and related to decadal-scale temperature variations,” while also relating current treeline positions to former treeline locations “by documenting in-situ remnants of relict stumps and logs.”

The results showed two main pulses of northward treeline advance in the mid- and late-twentieth century. The first of these recruitment phases occurred between 1940 and 1960, and the second started around 1972 and lasted into the 1980s. These treeline advances corresponded closely to annual decadal-scale temperature increases. The two researchers note “the lack of germination events prior to the mid-20th century indicates this is an exceptional advance,” but the relict stumps and logs found at most sites “show that this advance is part of a long-term reforestation process of tundra environments.” They note, for example, “stumps and logs of *Larix sibirica* can be preserved for hundreds of years (Shiyatov, 1992),” and “above the treeline in the Polar Urals such relict material from large, upright trees were sampled and dated, confirming the existence, around AD 1000, of a forest treeline 30 m above the late 20th century limit (Shiyatov, 2003).” They also state, “this previous forest limit receded around 1350, perhaps caused by a general cooling trend (Briffa, 2000; Esper *et al.*, 2002.”

“Synchronous with the advance shown from the western Siberian network,” Esper and Schweingruber write, a mid-twentieth century tree recruitment period was occurring in “central Sweden (Kullmann, 1981),

northern Finland (Kallio, 1975), northern Quebec (Morin and Payette, 1984) and the Polar Urals (Shiyatov, 1992).” Considering this with their own results from Asia, they conclude, “these findings from Europe and North America support a circumpolar trend, likely related to a global climate warming pattern,” thereby recognizing these data demonstrate the positive response of the biosphere to the warming that accompanied the demise of the Little Ice Age and the establishment of the Current Warm Period.

The international team of Kremenetski *et al.* (2004), composed of Russian, German, and U.S. scientists, conducted a multi-proxy study of climate-related factors in the Khibiny Mountains in the central part of the Kola Peninsula (67–68°N, 33–34°E), analyzing and dating a series of subfossil soil profiles buried in avalanche cones and living and subfossil pine trees. The researchers report finding “a period of exceptionally warm and dry conditions commenced at ca. AD 600 and was most pronounced between ca. AD 1000 and 1200.” They note, “warmer summer temperatures during this period (coeval with the ‘Medieval Warm Period’ observed in other parts of Europe) are evident in a 100–140 m upward shift in the pine (*Pinus sylvestris* L.) limit.” Applying a simple environmental lapse rate of 0.7°C/100 m to this finding, they state, “this warming can be estimated as being on the order of at least 1°C compared to the modern summer temperature.” In addition, they report, “on average, the cellulose of pine trees that grew between ca. AD 1000 and 1300 is enriched by $\delta^{13}\text{C}$ values of around 1 [per mil] compared to the modern trees from the region, further suggesting warmer summer climate than at present.” They also report “there was also a stabilization of slopes on avalanche cones and formation of soils on them” during this warmer and drier period. Finally, they note “this period of warming extends to northwestern Russia as well as other parts of Europe.”

Solomina and Alverson (2004) reviewed and synthesized the findings of papers presented at a conference held in Moscow in May 2002, which brought together more than 100 local paleo-environmental researchers from Bellarussia, Estonia, Georgia, Kyrgyzstan, Russia, Ukraine, and Uzbekistan, plus another 30 scientists from 18 other countries. The two researchers summarized the meeting’s overall findings for five distinct regions: the Arctic and Sub-Arctic, the Russian Plain and Caucasus, Central Asia and the Caspian Region, Eastern and Southern Siberia, and the Far East.

The Arctic and Sub-Arctic. “The 9th–14th

centuries were relatively warm, though at least two colder periods probably occurred in the 11th and 13th centuries,” after which “the 15th-early 20th centuries were generally cold,” and “subsequent warming is recorded with almost all proxies.”

The Russian Plain and Caucasus. “The climate of the Russian plain was relatively warm from the 11th to 14th centuries, with the exception of the late 12th-early 13th centuries, and colder from the 15th to 19th centuries, except for a warm interval in the first half of the 16th century.” In the Central Caucasus, they also report the existence of a “relatively warm climate around the end of the first to the beginning of the second millennium AD,” followed by “numerous glacier advances ... during the 14th-19th centuries,” the timing of which correlates well with glacier advances in the European Alps.

Central Asia and the Caspian Region. “A milder, less continental climate with more precipitation approximately from the 9th to 12th centuries” was indicated by most of the available data, and “cold conditions dominated from the 13th to 19th centuries, though interrupted by a brief warm period from the end of the 14th-early 15th century,” after which “the coldest conditions were probably in the 17th and 19th centuries, when glaciers advanced several times, lake level was high, and permafrost depth increased.”

Eastern and Southern Siberia. “Two periods of warmer and drier climate can be roughly identified in this huge area as having occurred from the 9th to 11th centuries and in the 14th century,” and “the 15th-19th centuries were clearly cold and the 20th century has seen a return to warm conditions.”

The Far East. “There is some evidence suggesting moderately warm conditions in the North Pacific region from the end of the first to the beginning of the second millennium,” with “a subsequent cooling after the 14th century.”

Summarizing their findings for the bulk of Northern Eurasia, Solomina and Alverson write, “a number of records allow one to distinguish the climatic pattern of the 9th-13th centuries [i.e., the Medieval Warm Period] from earlier and later colder conditions [i.e., the Dark Ages Cold Period and Little Ice Age, respectively].” They also note “the spatial pattern of temperature anomalies ca. 1000 years ago is similar to the earlier mid-Holocene ‘optimum.’” They write, “the warming of the 14th century in several regions, including the Russian plain, Altai and Central Asia, was at least as intense as the earlier one at ca. 1000 years before present or even warmer.” The latter widely detected event might correspond to what

some have called the Little Medieval Warm Period, or it may be the final years of the Medieval Warm Period before it relinquished control of Earth’s climate to the Little Ice Age.

Kalugin *et al.* (2005) analyzed sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia (51°42.90’N, 87°39.50’E), producing a multi-proxy climate record spanning the past 800 years. This record revealed several distinct climate periods over the past eight centuries. The regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, temperatures cooled, reaching peak deterioration between 1660 and 1700, which “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).” Recovery to prior-level warmth did not occur until late in the twentieth century.

With respect to moisture and precipitation, Kalugin *et al.* state the period between 1210 and 1480 was more humid than today, whereas the period between 1480 and 1840 was more arid. In addition, they report three episodes of multi-year drought (1580–1600, 1665–1690, and 1785–1810). These findings agree with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al.*, 1996; Panyushkina *et al.*, 2000). Their findings prove problematic for those who claim global warming will lead to more severe droughts, as all of the major multi-year droughts detected in this study occurred during the cool phase of the 800-year record.

Mackay *et al.* (2005) analyzed paleolimnological data obtained from a sediment core taken from the south basin of Lake Baikal, Russia, to reconstruct the climatic history of this area of central Asia over the past millennium. Their use of cluster analysis identified three significant zones of variability in the sediment core coincident with the Medieval Warm Period (c. 880 AD to c. 1180 AD), the Little Ice Age (c. 1180 AD to 1840 AD), and the Current Warm Period. The seven scientists say their diatom data supported the idea that “the period known as the MWP in the Lake Baikal region was a relatively warm one.” Following the MWP, diatom species shifted toward taxa indicative of colder climates, implying maximum snow depth values during the Maunder Minimum (1645–1715 AD), after which the diatom-derived snow accumulation data indicated a warming trend in the Lake Baikal region that began as

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early as c. 1750 AD. That the warming began around 1750 AD, nearly 100 years before the modern rise in atmospheric CO₂ concentration, suggests the planet's current warmth is the result of nothing more than the most recent and expected upward swing of this natural climatic oscillation.

Mazepa (2005) notes “dead trees located above the current tree-line ecotone provide evidence of the dynamic behavior in the location of the tree line in the recent past (Shiyatov, 1993, 2003)” and “previous studies have concluded that increases in tree-line elevation, and associated increases in tree abundance within the transient tree-line ecotone, are associated with extended warm periods (Tranquillini, 1979; Kullman, 1986; Payette *et al.*, 1989; Lloyd and Fastie, 2003; Lloyd *et al.*, 2003; Grace *et al.*, 2002; Helama *et al.*, 2004).”

Mazepa evaluated the uniqueness of Polar Ural tree-line and density response “to what is widely considered to be anomalous 20th-century warming,” examining evidence of tree growth dynamics along a continuous altitudinal transect 860 meters long and 40–80 meters wide on the eastern slope of the Polar Ural Mountains (66°48'57"N, 65°34'09"E) by repeating what Shiyatov had done four decades earlier. Mazepa discovered “a large number of well-preserved tree remains can be found up to 60–80 meters above the current tree line, some dating to as early as a maximum of 1300 years ago,” and “the earliest distinct maximum in stand density occurred in the 11th to 13th centuries, coincident with Medieval climatic warming,” when “summer air temperatures may have been 0.42–0.56°C warmer than they were over the last decades of the 20th century.”

Andreev *et al.* (2007) analyzed pollen and charcoal stratigraphy in a sediment core extracted from the central and deepest part of Lake Teletskoye in the northeastern part of the Altai Mountains in southern Siberia (51°43'N, 87°39'E), developing what they describe as “the first detailed climate and vegetation reconstruction for the last millennium in the northern Altai Mountains” (see Figure 4.2.4.4.3.1).

They found “dense Siberian pine forest dominated the area around the lake at least since ca. AD 1020,” when “climate conditions were similar to modern.” Then, “between AD 1100 and 1200, a short dry period with increased fire activity occurred,” and

“around AD 1200, climate became more humid with the temperatures probably higher than today.” This period of relatively stable climate, “possibly reflecting [the] Medieval Warm Epoch, lasted until AD 1410,” after which “slightly drier climate

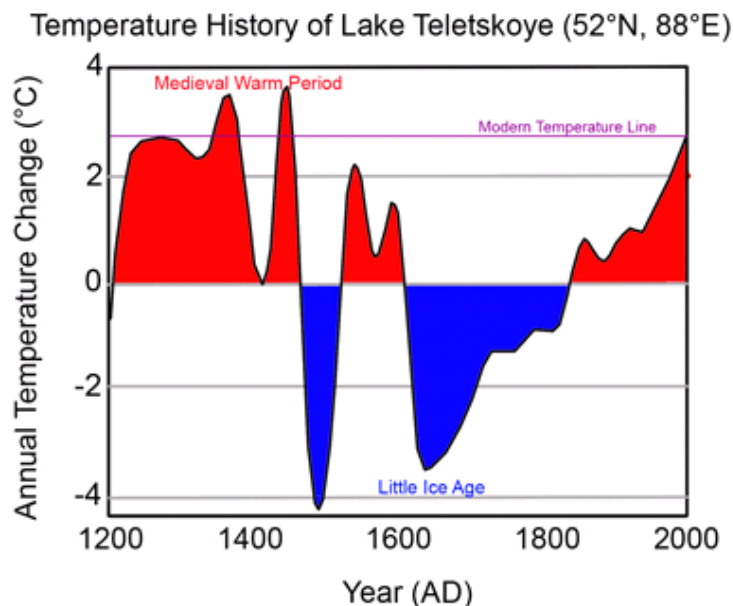


Figure 4.2.4.4.3.1. Proxy temperature record of Lake Teletskoye in the northeastern part of the Altai Mountains in southern Siberia. Adapted from Andreev, A.A., Pierau, R., Kalugin, I.A., Daryin, A.V., Smolyaninova, L.G., and Diekmann, B. 2007. Environmental changes in the northern Altai during the last millennium documented in Lake Teletskoye pollen record. *Quaternary Research* 67: 394–399.

conditions occurred between AD 1410 and 1560.” Thereafter, “a subsequent period with colder and more arid climate conditions between AD 1560 and 1820 is well correlated with the Little Ice Age,” after which the evidence indicated a climate warming they “inferred from the uppermost pollen spectra, accumulated after AD 1840,” which was “consistent with the instrumental data” of the modern period.

It is clear from Andreev *et al.*'s findings that the Altai Mountain region of southern Siberia displays the characteristic millennial-scale cycling of climate, from Medieval Warm Period to Little Ice Age to Current Warm Period conditions, that is characteristic of most of the rest of the world. That temperatures in the region from approximately AD 1200 to 1410 were “probably higher than today” provides yet another example of times and places when and where low-CO₂ Medieval Warm Period temperatures were likely higher than high-CO₂ Current Warm Period

temperatures.

Kalugin *et al.* (2007) collected several sediment cores from the deepest area of Teletskoye Lake and measured the spectra of numerous elements—including Ba, Cd, Ce, I, La, Mo, Nb, Rb, Sb, Sn, Sr, Th, U, Y, and Zr—after which “artificial neural networks (Veelenturf, 1995) were used for reconstruction of annual temperature and precipitation by sediment properties (Smolyaninova *et al.*, 2004).” The six scientists state, “a global cold period, the Little Ice Age with Maunder minimum, is clearly designated in their data, as well as global warming during the 19–20th centuries,” implying the existence of the Medieval Warm Period that preceded the Little Ice Age. Their plot of the data (see Figure 4.2.4.4.3.2) shows the mean peak temperature of the latter part of the Medieval Warm Period was about 0.5°C higher than the mean peak temperature of the Current Warm Period, which occurred at the end of the record.

Matul *et al.* (2007) studied the distributions of siliceous microflora (diatoms), calcareous microfauna (foraminifers), and spore-pollen assemblages found 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 research revealed, in the words of the five Russian scientists, “(1) the warming at the beginning of the Common Era (terminal epoch of the Roman Empire) during ~1600–1900 years BP; (2) the multiple, although low-amplitude, cooling episodes at the beginning of the Middle Ages, 1100–1600 years BP; (3) the Medieval Warm Period, ~600–1100 years BP; (4) the Little Ice Age, ~100–600 years BP, with the cooling maximum, ~150–450 years BP; and (5) the ‘industrial’ warming during the last 100 years.” They conclude, “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, the Medieval warming exceeded the recent ‘industrial’ one.”

Sidorova *et al.* (2007) developed a history of trunk radial growth increment of larch (*Larix gmelinii* Rupr.) trees in the middle reaches of the Bol’shoi

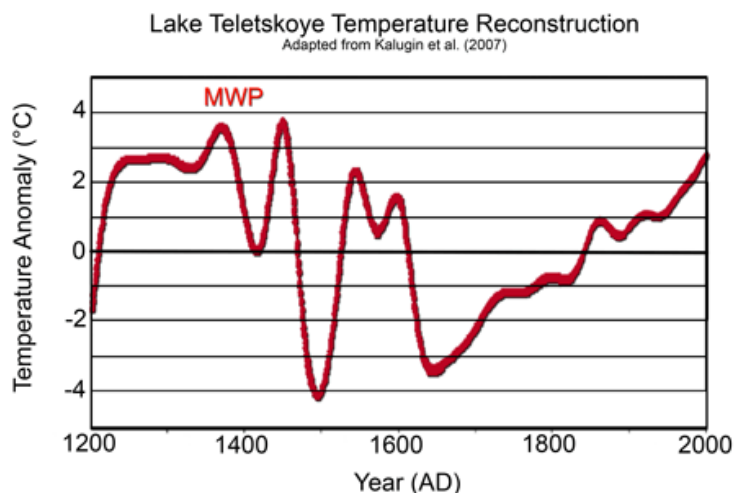


Figure 4.2.4.4.3.2. Proxy temperature record of Lake Teletskoye in the Altai Mountains in southern Siberia. Adapted from Kalugin, I., Daryin, A., Smolyaninova, L., Andreev, A., Diekmann, B., and Khlystov, O. 2007. 800-yr-long records of annual air temperature and precipitation over southern Siberia inferred from Teletskoye Lake sediments. *Quaternary Research* 67: 400–410.

Avam River on the northern edge of the Putoran Plateau, central Taimyr (70°30'N, 93°01'E), for the period AD 886–2003, which they found to be correlated with summer air temperature. This work revealed a period from the start of the record to approximately AD 1200 when inferred temperatures were generally much greater than those of the final decades of the twentieth century.

MacDonald *et al.* (2008) conducted an analysis of past changes in the location of the northern Russian treeline, as reconstructed from tree-ring data and radiocarbon-dated subfossil wood, to ascertain whether “the pattern of recent warming over the late nineteenth and the twentieth centuries caused significant changes in the density of trees at the treeline and/or an extension of the geographical location of the treeline.” They report “temperature increases over the past century are already producing demonstrable changes in the population density of trees, but these changes have not yet generated an extension of conifer species’ limits to or beyond the former positions occupied during the Medieval Warm Period (MWP: *ca* AD 800–1300) or the Holocene Thermal Maximum treeline extension (HTM: broadly taken here to be *ca* 10,000–3,000 years ago).”

On the Khibiny uplands of the central Kola Peninsula, for example, “the treeline was located 100–140 m higher in elevation than today during the MWP,” and “forest has yet to recolonize these

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elevations (Kremenetski *et al.*, 2004).” Of the northern Polar Urals they state, “the treeline was at its highest elevation during the MWP between *ca* AD 900 and 1300 when it reached 340 m,” after which it “descended to approximately 270 m during the Little Ice Age and then ascended to its present elevation of approximately 310 m during the recent warming of the late nineteenth and twentieth centuries.”

The three researchers conclude, “at the Russian sites studied, the impact of twentieth century warming has not yet compensated fully for the mortality and range constriction caused by the cold temperatures of the Little Ice Age,” and they note “these results are similar to observations in some other northern treeline regions such as uplands in eastern Quebec and interior Labrador where *Picea mariana* (P. Mill.) B.S.P. and *Picea glauca* (Moench) Voss trees remain below their pre-Little Ice Age limits despite recent warming (Gamache and Payette, 2005; Payette, 2007).”

Noting the long-term decrease in seasonal peaks of water levels allows human settlement of low geomorphic locations, such as river and lake floodplains, whereas a rise in flood levels causes settlements to be shifted to higher elevations, Panin and Nefedov (2010) noted “ancient settlements could not persist under the impact of regular inundations.” In a study of the Upper Volga and Zapadnaya Dvina Rivers of Russia, the two researchers determined “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.”

They found “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,” while noting “a model of past warming epochs can be the warming in the late 20th century.” 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.” They found the period AD

1000–1300 hosted the greatest number of floodplain settlements..

Panin and Nefedov argue 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.

Noting dust storms are common features adjacent to the Aral Sea, Huang *et al.* (2011) investigated the grain-size distributions of wind-blown sediments found in a core retrieved from that water body while “attempting to trace the variations in atmospheric dynamics in central Asia during the past 2000 years.” They focused on variations observed at the transition from the Medieval Warm Period to the Little Ice Age, since this period, they write, “is the most pronounced climatic transformation during the last millennium,” citing Yang B. *et al.* (2002), Trouet *et al.* (2009), and Chen *et al.* (2010). Their analysis revealed the history of dust deposition in central Asia can be divided into five distinct periods on the basis of their observations: “a remarkably low deposition during AD 1–350, a moderately high value from AD 350–720, a return to a relatively low level between AD 720 and AD 1400 (including the Medieval Warm Period), an exceptionally high deposition from AD 1400 to [the] 1940s and an abnormally low value since [the] 1940s.”

The first of these “distinct periods” coincides with the Roman Warm Period, the second with the Dark Ages Cold Period, the third (as Huang *et al.* note) with the Medieval Warm Period, the fourth with the Little Ice Age, and the fifth with the Current Warm Period. They found the temporal variation in dust deposition they observed was consistent with the “mean atmospheric temperature of the Northern Hemisphere during the past 2000 years, with low/high annual temperature anomalies corresponding to high/low dust supplied in the Aral Sea sediments, respectively.” The four researchers’ graphs of their wind intensity/dust storm data show the minimum values of these inverted measures of annual temperature during the Roman Warm Period, the Medieval Warm Period, and the Current Warm Period were all about the same.