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The Potential Impact of Cool Roof Technologies Upon Heat Wave Meteorology and Human Health in Boston and Chicago

ABSTRACT

Heat is the greatest weather-related killer in Boston and Chicago, as well as other large urban areas. Our goal is to determine whether increasing urban solar reflectance, through the use of reflective roof products, would lessen the intensity of extreme heat events and save lives during such events. We use a synoptic climatological approach that places days into air mass categories encompassing a wide variety of individual weather metrics including air temperature and dew point. The dry tropical (DT) and moist tropical plus (MT+) air masses are the most oppressive and deadliest. We identify and perform an air mass classification for four actual heat events in Boston and Chicago to determine whether a 0.15 and a 0.25 increase in roof surface reflectance would alter weather conditions during heat waves. These reflectance modifications are achievable in cities adopting reasonable urban heat mitigation strategies. For Boston and Chicago, reflective roofs reduce temperatures and dew points enough to generate actual changes in air mass type from DT and MT+ to more benign air masses that are not harmful to human health. In Boston, using the 0.25 reflectance increase, our modeling indicates that twelve lives would be saved during the four extreme heat events. For Chicago, we find that 42 lives would be saved using the same reflectance increase. Considering that ten to 15 such heat events could occur over a decade, we suggest that the use of reflective roofing products could potentially save hundreds of lives per decade during excessive heat events in each city.

Keywords

Urban heating, solar reflectance, cool roofs, air mass category, synoptic climatological approach, heat-related mortality

Introduction

Urban warming is a critical challenge that negatively impacts human health, quality of life, energy use, air quality, social equity, and economic prosperity. More than eight out of ten Americans currently live in an urbanized area [1] and, on average, urban spaces are heating up at twice the global rate [2]. The Fourth National Climate Assessment estimates with high confidence that urban heat islands in the United States lead to daytime temperatures that are 0.5° to 4°C higher and nighttime temperatures that are 1° to 2.5°C higher in urban areas than in rural ones, with wider differences in humid regions, larger cities, and areas with higher population density [3].

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The impact of excessive heat on human health cannot be underestimated. In many large urban centers in the United States, heat is the leading weather-related killer, greatly outstripping hurricanes, tornadoes, lightning, and blizzards [4]. It is estimated that approximately 1,500 heat-related deaths occur in the United States during an average summer, though the number is highly variable from year-to-year and can sometimes exceed 5,000 deaths [5].

The goal of our study is to quantify how increasing urban reflectance through the use of reflective roofing products would lessen the intensity of extreme heat events (EHE) and save lives in Chicago and Boston. Chicago and Boston were selected due to the vulnerability of these cities to negative health outcomes during EHEs, despite being widely considered "cool climate" cities. It is often not the intensity of the heat, but the variability of the summer weather that renders an urban area most vulnerable to excessive heat. We hypothesize that a reduction in temperature and Apparent Temperature[6] (AT) will cause a possible change in air mass type and a reduction in excess mortality.

Although EHEs are rare in Chicago and Boston, their presence often leads to a rapid increase in mortality since the urban structure of these cities is ill-equipped to allow for internal cooling of living space. Brick row homes and apartment buildings with traditional dark-colored asphaltic, slate, or tile roofing products, few windows, and often without air conditioning are perfect examples of structures that are not designed for EHEs. Conversely, hotter cities, such as Phoenix and Miami, often demonstrate low vulnerability to negative heat/health outcomes because these cities are always very hot in the summer; the low summer weather variability suggests that the population is behaviorally-adapted to excessive heat.

Literature Review

IMPACTS OF URBAN HEAT, COOL CITY STRATEGIES, AND URBAN HEAT MITIGATION

Heaviside et al. [7] provides a detailed review of the current research related to urban heat and health. Excess heat can lead to dehydration, heat exhaustion, and heat stroke but these conditions are only a small portion of the health challenges caused by heat. Heat has a more hidden impact by aggravating existing medical conditions such as diabetes, respiratory disease, kidney disease, and heart disease [8].

Stone et al. [9] estimates changes in heat-related deaths up to the year 2050 resulting from changes in vegetative cover and surface reflectance in Atlanta, Philadelphia, and Phoenix and finds that a combination of vegetation and reflectance enhancement could offset projected heat mortality increases by 40 to 99%.

THE RELATIONSHIP BETWEEN REFLECTIVITY AND TEMPERATURE

Santamouris' [10] comprehensive review on urban heating finds that when a global increase of the city's reflectivity is considered, the expected mean decrease of the average ambient temperature is close to 0.3°C per 0.1 increase in reflectivity,[7] while the corresponding average decrease of the peak ambient

[6] Apparent Temperature (AT) is defined as the temperature equivalent perceived by humans, caused by the combined effects of air temperature, dewpoint, and wind speed [6].

[7] Reflectivity is measured on a scale of 0 to 1. A surface with a reflectance of 0 absorbs all the incoming solar energy, while a surface reflectance of 0.5 means that the surface reflects 50% of the solar energy that contacts it while absorbing the other 50%.

temperature is close to 0.9°C. Many studies demonstrate that cool roofs reduce 2-meter (roughly head height from ground) urban temperatures by increasing the reflectance of incoming solar radiation [11].

There are also real-world examples of regional cooling resulting from higher reflectivity. Campra [12] compares weather station data in the Almeria region of Spain to similar surrounding regions. Almeria has a unique tradition of whitewashing its greenhouses, and thus, reflects more sunlight than neighboring regions. Over the 20-year study, researchers find that Almeria has cooled 0.8°C compared to the surrounding regions.

SYNOPTIC CLIMATOLOGICAL APPROACH

Synoptic climatological approaches have been utilized extensively within a large variety of heat/health studies [13]. The approach classifies days into one of a number of discrete "air mass" types that traverse a given area and provide unique weather characteristics to that area. Humans respond to an entire suite of weather variables that impact the individual simultaneously; the synoptic climatological approach is a more accurate way to evaluate human response to extreme weather, rather than analyzing temperature, humidity, and other meteorological variables separately. The holistic approach that a synoptic evaluation provides allows the researcher to pinpoint "offensive" conditions that lead to unusual human response, such as heat-related mortality [14].

Our research uses the "spatial synoptic classification" (SSC) [15] which incorporates observations of temperature, dewpoint, pressure, wind, and cloud cover four times daily for a particular location via a hybrid manual/automatic classification scheme, and classifies the days into an air mass type (Table 1) [16]. Two of these air masses, dry tropical (DT) and moist tropical plus (MT+) have been determined in many studies to be associated with statistically significantly higher mortality rates, particularly during the summer months [17].

Table 1. Summary of air mass type abbreviations and descriptions. Bold items indicate air mass types with statistically significantly higher mortality rates.

SSC Air Mass Type Abbreviation	Air Mass Type Description
DP	Dry Polar: cool, dry air mass
DM	Dry Moderate: comfortable and seasonally warm
DT	**Dry Tropical: hot, dry, and very oppressive**
MP	Moist Polar: cool and moist, overcast
MM	Moist Moderate: warmer than MP but still wet and overcast
MT	Moist Tropical: typical summer air mass, warm and humid
MT+, MT++	**Moist Tropical Plus: excessively hot and humid; oppressive**
TR	Transition between different air masses; frontal boundary

The SSC approach has been successfully employed within heat/health warning systems [18], climate change studies [19], and most recently in determining the impacts of changes in urban structure on cooling densely-populated cities [20]. This recent use of the SSC has suggested that, by utilizing highly-reflective materials on roofs and pavement and by incorporating more tree canopy within the urban area, we can actually change the character of some DT and MT+ days during intense heat waves to something less likely to produce negative health outcomes.

Methodology

DEVELOPING HEAT-HEALTH RELATIONSHIPS

We first determined the historical relationships between weather and heat-related mortality for each city. Our previous research has shown that each city reacts differently to heat in terms of the magnitude of negative health outcomes [16]. Cities vary considerably in terms of urban structure, demographics, and climate, all of which play a role in determining their vulnerability to heat/health issues. Thus, separate evaluations were developed for Boston and Chicago to determine their heat-related mortality vulnerabilities.

Heat-related mortality has generally been associated with the occurrence of the warmest air masses, MT+, MT++, and DT. As moist tropical air masses are fairly common in the summer across much of the mid-latitudes, the MT+ and MT++ subsets have been developed to describe more intense versions of the air mass.

As populations in different cities have different levels of acclimatization, the SSC categories are useful in that the mean conditions associated with the different weather types vary from place to place. Thus, an MT+ day in Chicago is very different from an MT+ day in New Orleans.

Using the SSC, daily air mass types have been determined for over 300 cities in the United States since 1948 (see [21]). For Boston and Chicago, the meteorological data utilized to determine air mass types were taken from Logan International Airport and O'Hare International Airport, respectively. Both locations provide the detailed hourly meteorological data necessary to develop our SSC analysis. Although Logan is located adjacent to a large water body, there is no problem using such data for air mass identification. Air masses are macro-scale phenomena, which suggests that, if an MT+ is located over Boston, it is located over the entire urban area. Thus, the more micro-meteorological events that might impact a coastal location have little impact on overall air mass delineation.

Daily mortality data were obtained from the National Center for Health Statistics, which included information on the cause, place (county), date of death, age, and race [22]. These data were extracted for summer only (May 1 through September 30) for Chicago and Boston for the years 1985 – 2010. Total daily mortality across the cities' standard metropolitan statistical area were summed for each day and then standardized to account for demographic changes in the population characteristics during the period (see [23]). The mortality for each day is expressed as a variation above or below a standardized baseline.

After standardization, mean anomalous daily mortality[8] was calculated for each air mass type. In both Chicago and Boston the DT, MT+, and MT++ air masses were associated with the greatest increase in mortality over baseline levels. However, not all days within these air masses demonstrate elevated mortality, so a stepwise linear regression was developed for each city to determine which variables accounted for this mortality variation. The independent variables used in our analysis were meteorological (e.g., morning and afternoon temperature, dew point, wind speed, and cloud cover), persistence-oriented,[9] and seasonal (time of season).[10] This statistical procedure resulted in an algorithm for each city

[8] Mean anomalous daily mortality is the number of deaths above what would normally by expected on that day.
[9] How many consecutive days of the air mass are occurring within the EHE.
[10] June EHEs have shown to be more deadly than similar EHEs in September.

containing statistically significant independent variables. It was utilized to estimate mortality during particular EHEs both in reality and under modeled simulations.

Upon the establishment of heat/health algorithms, we then selected four important EHEs for each city based on their character and seasonality. Since EHEs are physically different, some being very humid and others being excessively dry, we chose different types of events, from the most extreme to somewhat common. Finally, we wanted EHEs from different times in the season, including early and late season events. This is important because late season EHEs frequently exhibit lower excess mortality than early season counterparts with the same magnitude of oppressive weather [24].

After the EHEs were selected for each city, they were evaluated in terms of baseline meteorology and a determination of the air mass present. Using the algorithms described above for each city, we estimated the daily excess mortality attributed to heat for each day within the EHEs. This resulted in an established baseline from which to determine how the modeling of each city, based upon increased urban reflectance, would impact the meteorology, air mass type, and associated daily excess mortality for each of the newly-modeled EHEs.

ESTIMATING EFFECTS OF HIGH REFLECTANCE MITIGATION SCENARIOS ON LOCAL METEOROLOGY

Once relationships between local meteorology and heat-mortality were established for each city, we used mesoscale meteorological modeling to estimate the effects of various heat-mitigation strategies (e.g., increasing urban reflectance) on the diurnal course of ambient air temperature and dewpoint temperature.

We used the Weather Research and Forecasting (WRF) model, version 3.8.1, for regional (mesoscale) atmospheric simulation of urban environments (see [25]). We modeled each urban area using four nested grids with resolutions ranging from 27 kilometers (km) for the outermost grid down to 1 km for the innermost grid. The outermost domain typically had an extent of 1,500 to 2,000 km in both the North-South and East-West directions. Each of the nested domains included approximately 100 grid cells in each direction. Simulations for each city used a time step (for the outer domain) of one minute. To ensure appropriate model spin-up, the simulation of the outermost domains was run for a seven-day period, at which time the finer domains were initiated for an additional four-day period.

~~Figure 1. Domain configurations for (a) Boston and (b) Chicago, each showing four nested domains.~~

Baseline simulations for each city and each EHE were simulated and validated against data from a local National Weather Service weather station for the same period of time. The validated baseline models were then modified to represent different scenarios of reflectance modification (REFL1 and REFL2). These test cases were simulated by modifying the reflectance of individual urban facets (roofs and roads) for each of the three categories of urban development. Roofs and roads for the baseline simulations were assigned a reflectance value of 0.15. The REFL1 case represented an overall reflectance increase by 0.15 (to 0.30), while the REFL2 case corresponded to an overall 0.25 increase in reflectance (to 0.40). These increases in reflectance were implemented in the model through modifications of roof and road surface reflectance across low, medium, and high intensity categories of urbanized land cover.

The low, medium, and high intensity development categories used in the modeling are based on fraction of impervious surface as defined in the National Land Cover Database (NLCD) as described in Homer et al. [26]. Low intensity urban land cover corresponds to areas with a mix of constructed materials and vegetation, with impervious surfaces accounting for 20 to 49% of total cover (typically single-family housing units). The medium intensity urban land cover includes areas with 50 to 79% impervious surface cover (typically higher density housing). The high intensity classification is for areas with 80 to 100% impervious cover (typically commercial and industrial areas). This overall increase in modeled urban reflectance was accomplished by increasing road reflectance to 0.30, which is reasonably obtained through a variety of currently-available paving techniques.[11] The reflectance of rooftops was modified such that the overall urban surface reflectance (accounting for fraction of urban areas covered by roofs and paving) would be either 0.30 or 0.40, for cases REFL1 and REFL2, respectively.

The REFL1 and REFL2 scenarios were selected to model the sensitivity of the composite urban reflectance of cool roof solar reflectance, roughly mimicking the current span in aged solar reflectance values for cool roofing products that meet California's Title 24, Part 6; CALGreen (Title 24, Part 11); or ENERGY STAR® requirements.

At the completion of each simulation (for each EHE and for each simulation case), hourly data from the finest model grid domain were exported for urban grid cells using a specialized script. The hourly values of air temperature and dewpoint temperature perturbations were then provided for input to the previously developed heat/health relationships to estimate the effects of the projected changes on heat-related mortality.

The results of the REFL1 and REFL2 modeling are compared to the baseline values to determine how these increases in reflectance have altered the meteorology, air mass character, and associated excess heat-related mortality. Based on our hypothesis, we expect a reduction in temperature and AT, a possible change in air mass type from more to less oppressive, and a reduction in excess mortality. These values have rarely been quantified, which will hopefully provide value as to how reflective materials can influence meteorology and negative health outcomes during EHEs.

Results and Discussion

MORTALITY ALGORITHM DEVELOPMENT

For each city we determined which air mass types are most likely to produce heat-related mortality (Table 2). The DT, MT, and MT+ days all show the greatest increases in daily mortality totals, and in some cases, these can exceed six extra deaths per day. The other air masses (e.g., DP, DM, and MP) show mortality deviations below baseline values. When the oppressive air masses occur earlier in the summer season they show a higher disparity than later in the summer season; this is a typical result that we find in many mid-latitude cities.

Table 2. Mean daily variations in mortality around the standardized baseline for each air mass type in each summer month in Boston. Bold numbers indicate ~~higher positive~~ disparities greater than 5.0 ~~darker green numbers are higher negative disparities~~.

[11] The solar reflectance of concrete is typically 0.25 to 0.30.

	Dry Moderate (DM)	Dry Polar (DP)	Dry Tropical (DT)	Moist Moderate (MM)	Moist Polar (MP)	Moist Tropical (MT)	Transition (TR)	Moist Tropical + (MT+)
May	-1.3	-1.1	4.9	-2.2	-2.7	3.7	-1.5	**5.9**
June	-0.4	-1.8	**6.6**	-1.5	-2.3	3.0	-0.4	**6.2**
July	-1.5	-1.7	**7.8**	-0.6	-3.8	3.3	1.1	**5.7**
August	-1.4	-1.8	**5.4**	-1.8	-3.8	1.6	0.6	3.5
September	-1.9	-3.8	0.1	-1.6	-2.3	1.9	-2.7	3.2

In addition, consecutive days of the oppressive DT and MT+ air masses show increasingly higher positive deviations (Table 3). By the seventh consecutive day, average daily mortality is over five times higher than on the first day of oppressive air mass intrusion.

Table 3. Mean daily variations in mortality during consecutive day runs of DT and MT+ air masses in Boston.

Day in Sequence	Excess Deaths
1	2.9
2	5.2
3	7.3
4	9.7
5	11.7
6	13.9
7	16.2

After isolating the days with DT, MT+, and MT++ air masses during the period of record, we can develop an algorithm that estimates positive mortality disparities on each oppressive air mass day using a stepwise linear regression approach. The algorithm developed for Boston is shown in Eq 1.

$$M = -1.36 + 2.243\,DIS + 0.154\,AT17 - 0.011JD \#(1)$$

Where:

M = excess daily mortality during oppressive air mass days,

DIS = day in sequence,

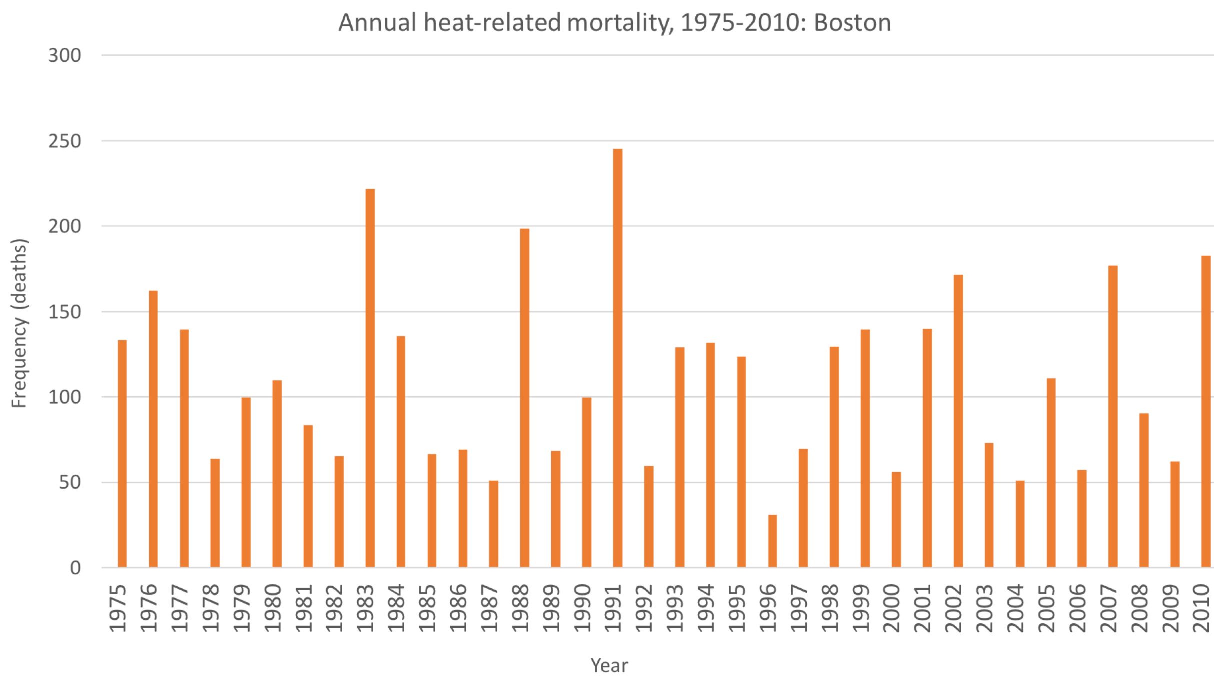
$AT17$ = the AT at 5PM (°C), and

JD = Julian date, where May 1 is 1, May 2 is 2, June 1 is 32, and so on.

The JD variable is inversely related to M and indicates that, as the season wears on, the same intensity EHE will cause lesser mortality. This is not an uncommon result in our research (see [16]) since the population acclimatizes to the heat as the summer progresses, and there is a "mortality harvesting" component, where early season heat deaths result in a lesser number of susceptible individuals available to die later in the season.

Thus, each oppressive air mass day has an estimated excess mortality that is largely attributed to heat-related causes. These can be added for each summer season to determine the estimated heat-related death totals annually (see Figure 1). These values vary considerably from one summer season to the next, and are dependent upon the number of oppressive air mass days, the length of consecutive day EHEs, and AT. Some years have fewer than 50 seasonal deaths, while others can exceed 200.

Figure 1. Total estimated heat-related mortality for each summer season in Boston using the developed algorithm.



A similar analysis for Chicago produced the algorithm displayed in Eq 2.

$$M = -26.74 + 4.62\ \mathrm{DIS} + 0.777\ \mathrm{AT16}\#(2)$$

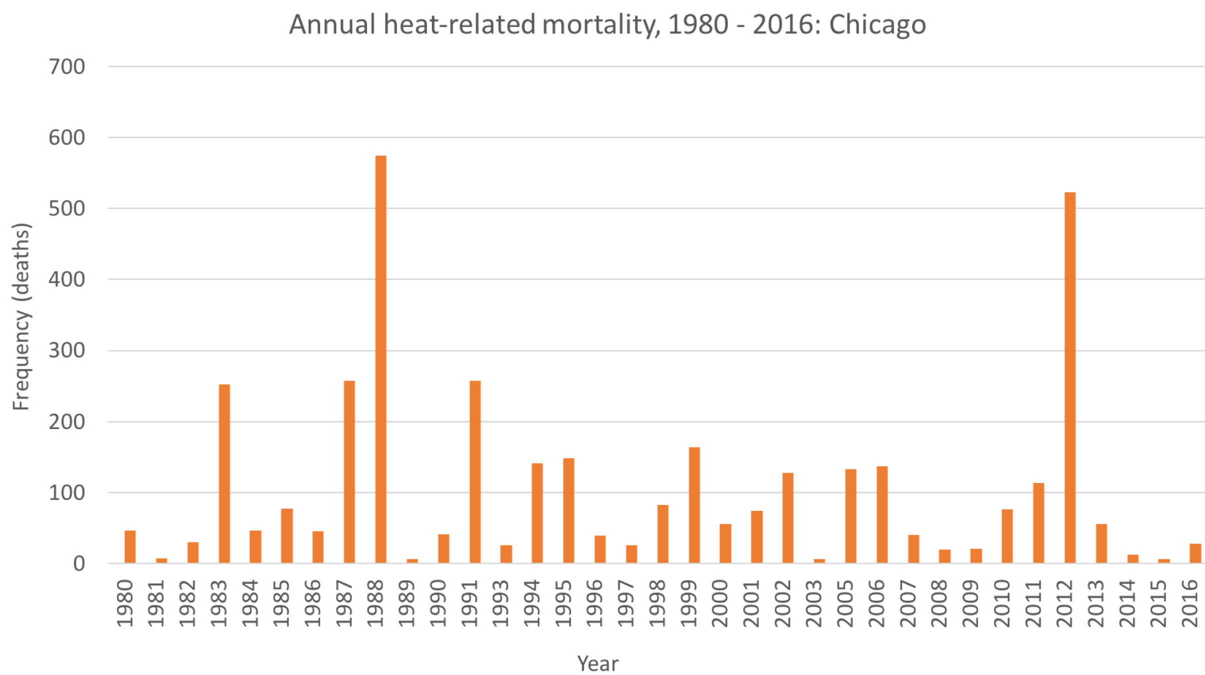
Where:

DIS = day in sequence, and

AT16 = the AT at 4PM (°C).

Much like Boston, we can estimate seasonal excess or heat-related mortality for Chicago (Figure 22).

Figure 2. Total estimated heat-related mortality for each summer season in Chicago using the developed algorithm.



During typical summers Chicago's seasonal heat-related mortality is higher than Boston's; it averages slightly over 100 deaths per summer with a very high standard deviation. However, during extreme years (1988 and 2012), Chicago totals far exceed any that are estimated for Boston. Thus, on an inter-seasonal basis, variations in Chicago heat-related mortality are even more variable than those in Boston.

The Chicago mortality estimates returned a relatively low number of deaths during the 1995 EHE, the worst in the city's recorded history. During that singular event in mid-July of 1995, it is estimated that 800 people perished from the heat [27]. Our model significantly underestimated that total. We will discuss the reasons for this later in the paper.

BOSTON SIMULATION RESULTS

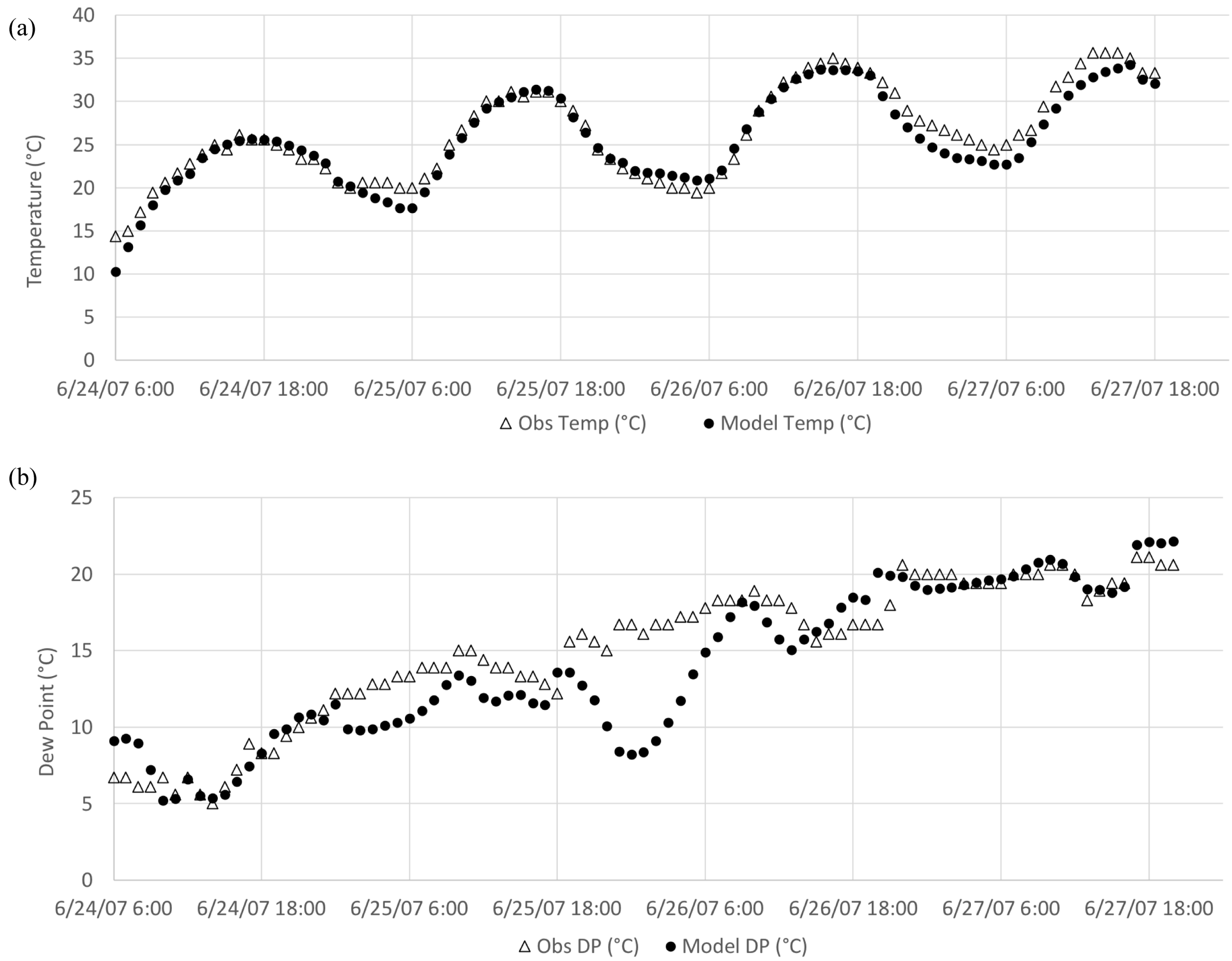
For the Boston simulations, we selected these four EHEs for evaluation: July 19-23, 1994; July 16-18, 1999; August 12-18, 2002; and June 25-28, 2007 (see Table 4). The selection was predicated upon finding meteorologically different types of EHEs to determine whether responses to our reflective roof scenarios were similar or different across events. For example, the July 1994 event is hot, humid, and dominated by MT days. The July 1999 event was hot and dry with all DT days. The August 2002 and June 2007 events were mixtures of hot and dry and hot and humid days. For the June 2007 event we wanted to observe potential differences in this early season EHE.

Table 4. Daily maximum, minimum, and dewpoint temperatures for the four Boston EHEs.

Date	Temperature, Max, °C	Temperature, Min, °C	Average Dewpoint, °C	Air Mass Category
1994-07-19	31.67	20.00	20.00	MT
1994-07-20	33.90	22.78	21.11	MT
1994-07-21	35.56	23.89	22.78	MT++
1994-07-22	33.90	23.89	22.22	MT+
1994-07-23	32.78	22.22	21.67	MT
1999-07-16	35.00	21.11	17.78	DT
1999-07-17	36.67	23.89	20.56	DT
1999-07-18	36.11	22.78	20.00	DT
2002-08-12	32.22	21.11	18.89	MT
2002-08-13	36.11	22.78	19.44	DT
2002-08-14	37.78	25.00	19.44	DT
2002-08-15	33.90	22.78	20.56	MT+
2002-08-16	33.90	25.00	22.22	MT++
2002-08-17	35.56	25.56	17.78	DT
2002-08-18	35.00	22.22	20.00	DT
2007-06-25	31.67	18.33	13.89	DT
2007-06-26	35.00	19.44	17.78	DT
2007-06-27	35.56	24.44	20.00	MT++
2007-06-28	33.33	24.44	20.00	MT+

Our baseline simulation was developed for the June 2007 EHE to determine if the modeled baseline simulation closely duplicates reality. We gathered the necessary airport meteorological data (Logan Airport, a first order meteorological station), extracted the simulation output (for Logan), and compared the model output with observed data for the June 2007 EHE (see Figure 3). The root mean square error for air temperature and dewpoint estimates are 2°C and 2.4°C, respectively. The comparison graphs show how well the control simulation duplicates reality, with one exception of a few hours overnight on June 25, 2007.

Figure 3. Comparison of model-predicted (a) temperature and (b) dew point with observations for the control simulation for Boston, June 25 – 28, 2007.



The simulations for the June 2007 EHE exemplify the results that we uncovered for the four EHEs (Table 5). The modeling demonstrates a significant cooling, particularly during daytime hours. Not surprisingly, the magnitude of cooling is greatest for the REFL2 scenario, where urban reflectance was increased by 0.25. In some cases, cooling approaches and even exceeds 1.5°C using the REFL2 scenario, and is greater than 0.6°C under the REFL1 scenario. The decreases under the REFL2 scenario are quite important, as this magnitude of cooling is sometimes sufficient to prevent some deaths from heat-related causes.

Table 5. Six-hourly data output (air temperature and dewpoint temperature) for REFL1 and REFL2 scenarios for the June 2007 EHE in Boston. Data correspond to the grid cell containing Logan Airport. Italicized items indicate values above baseline. Items in bold and shaded gray indicate 1.00° C or greater below or above baseline.

Local Time	Baseline Temperature, °C	Base Dew Point, °C	REFL1 Temperature, °C	REFL1 Dew Point, °C	REFL2 Temperature, °C	REFL2 Dew Point, °C
6/24/07 at 5:00	9.65	9.03	9.65	9.03	9.64	9.03
6/24/07 at 11:00	20.86	5.31	20.36	*5.62*	**19.81**	*6.02*
6/24/07 at 17:00	25.63	7.43	25.26	7.14	24.91	7.01
6/24/07 at 23:00	22.84	10.47	22.34	10.53	**21.36**	***11.47***
6/25/07 at 5:00	17.67	10.32	17.13	10.18	**16.57**	*9.86*
6/25/07 at 11:00	27.56	13.06	26.96	*13.33*	**26.33**	*13.84*
6/25/07 at 17:00	31.28	11.46	30.56	***13.23***	**29.99**	***13.12***
6/25/07 at 23:00	22.93	8.4	22.83	*9.23*	22.33	***10.02***
6/26/07 at 5:00	20.87	13.46	20.84	13.28	20.66	13.19
6/26/07 at 11:00	30.33	16.86	**29.33**	***17.98***	**28.52**	***18.11***
6/26/07 at 17:00	33.67	17.84	33.29	17.28	32.86	17.22
6/26/07 at 23:00	25.71	19.26	25.51	*19.56*	25.39	19.28
6/27/07 at 5:00	22.74	19.59	22.43	19.60	22.37	19.59
6/27/07 at 11:00	30.73	20.7	29.91	*21.00*	**29.16**	*21.44*
6/27/07 at 17:00	32.54	21.93	31.95	*22.2*	**31.41**	*22.21*

~~**Figure 4. Hourly plots of temperature (a) and dewpoint (b) between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Boston, June 24 – 27, 2007. Positive values indicate lower simulation values than the baseline (thus, a modeled reduction in values); negative values indicate higher simulation values than the baseline.**~~

Dewpoint temperatures do not show the systematic reduction we see with air temperature. In some cases, there are modest to moderate increases in dewpoint temperature, sometimes exceeding 1°C. This is related to the vertical motion of air (ventilation) during very hot conditions. If temperatures near the surface are reduced, ventilation is inhibited; even a small reduction in vertical motion can lead to the accumulation of more humid air near the surface resulting from evapotranspiration from vegetation, emissions from vehicles, and other sources of moisture. We have seen this occurrence consistently in our previous evaluations (e.g., [20]). Nevertheless, even with modestly rising dewpoint temperatures, AT is less at virtually all of the times, even in those unusual circumstances when dewpoint temperature increases at the same rate that the air temperature decreases. For example, on June 26 at 11AM, the AT for the baseline temperature/dewpoint combination of 30.33°C/16.86°C is 31°C. For the REFL2 scenario, the AT for a temperature/dewpoint combination of 28.52°C/18.11°C is only 29°C. Thus, the increased dewpoint has much less of an impact on AT than does a corresponding temperature decrease.

A summary of all four EHEs shows consistency among the events (see Table 6), although some important differences are noted. Afternoon (5PM) AT declines are greater for the REFL2 scenario as compared to REFL1; the difference can sometimes exceed 3°C, as is the case on August 13, 2002. In addition, there are occasions when the air mass actually changes. For example, during the June 2007 EHE, the first day of that EHE was originally a DT day, and because of AT reductions, it was altered to a much less oppressive DM day under the REFL1 scenario, and to a typical and more comfortable MT day under the REFL2 scenario.

Table 6. A summary of results for all four evaluated EHEs in Boston. Boxes shaded in light gray represent air mass changes.

	Baseline			**REFL1**			**REFL2**		
EHE #1	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
June 25, 2007	26.6	DT	3	26.2	DM	0.7	25.9	MT	0.7
June 26, 2007	31.7	DT	6.1	31.3	DT	3.8	30.5	DT	3.6
June 27, 2007	31.5	MT+	8.3	31.2	MT+	6	30.6	MT+	5.9
June 28, 2007	29.8	MT+	10.2	29.6	MT+	8	29.4	MT+	7.9
			27.6			**18.5**			**18.1**
EHE #2	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 13, 2002	33.6	DT	6.3	32.5	MT+	6.1	30	MT+	4.8
August 14, 2002	36.4	DT	9	36.1	DT	8.9	35.9	DT	8.9
August 15, 2002	31.4	MT+	11.2	31.1	MT+	11.2	30.8	MT+	11.1
August 16, 2002	32.7	MT+	13.4	32.2	MT+	13.4	31.7	MT+	13.4
			39.9			**39.6**			**38.2**
EHE #3	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 19, 1999	30.1	MT	3.8	29.9	MT	3.8	29.7	MT	3.7
July 20, 1999	30.3	MT	3.8	29.4	MT	3.8	28.5	MT	3.7
July 21, 1999	33.9	MT+	6.6	33.5	MT+	6.5	32.9	MT+	6.5
July 22, 1999	32.2	MT+	8.8	31.8	MT+	8.8	31.5	MT+	8.7
July 23, 1999	21.3	MT	4.3	20.7	MT	4.3	20.4	MT	4.2
			27.3			**27.2**			**26.8**
EHE #4	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 16, 1999	31.7	DT	6.3	31.4	DT	6.3	31.1	DT	6.2
July 17, 1999	35.3	DT	9.1	35	MT+	9.1	34.5	MT+	9
July 18, 1999	33.8	DT	11.3	33.8	MT+	11.3	33.4	MT+	11.2
			26.7			**26.7**			**26.4**
TOTAL EXCESS MORTALITY			**121.5**			**112**			**109.5**
TOTAL PERCENT REDUCTIONS						**8%**			**10%**

There were three other daily air mass changes noted in the four evaluated Boston EHEs: one during the August 2002 EHE and two others during the July 1999 EHE. In all of these cases, DT days were altered to almost equally-oppressive MT+ days. This is a possibility on days when there are temperature reductions and dewpoint temperature increases — something that was not uncommon in the EHEs evaluated for Boston. Thus, these modifications generally resulted in minor decreases in mortality.

The reduction of excess mortality is noted in all four EHEs, although the largest drop occurred in the June 2007 event when estimated mortality for the baseline was almost 28 deaths as compared to 18 deaths for the REFL2 scenario. The other three events demonstrated more modest declines of about 1 or 2 deaths. For the June 2007 event, the large decline is partially attributed to the change in the day in sequence (DIS) variable. Since the first day changed from an oppressive air mass to a non-oppressive one for both REFL scenarios, that set the DIS counter back one full day for both scenarios, resulting in more significant mortality reductions.

Total baseline mortality for the evaluated events was about 122 deaths. This was reduced to 112 for the REFL1 scenario and 109 for the REFL2 scenario, which represents an 8.1% reduction for the former and a 9.2% reduction for the latter. The twelve saved lives for the events under the REFL2 conditions may not initially seem impressive, but assuming that the number of EHEs similar to these over a 30-year period can exceed 40 or 50 events (about one to two per year on average), a total of 150 to 200 lives can be saved during this period if REFL2 conditions are achieved. This is not an insignificant number, considering that there are much larger potential decreases in emergency room visits and ambulance calls, which were not evaluated here.

CHICAGO SIMULATION RESULTS

Much like the Boston analysis, the four EHEs selected for the Chicago simulations were individually unique (see Table 7). For example, the early August 1988 event was a mixture of DT and MT+ days, while the event in mid-August was pure MT+. Since we were trying to determine how a more typical EHE might respond under the REFL scenarios, the mid-August 1988 event was not viewed as particularly extreme. The July 1995 event was the most historic in Chicago history; hundreds of people died during this heat wave. As with the July 1995 event, the July 2012 event was also very hot, but dewpoint temperatures were generally lower than the unprecedented 1995 EHE, and thus, mortality totals were lower.

Table 7. Daily maximum, minimum, and dewpoint temperatures for the four Chicago EHEs.

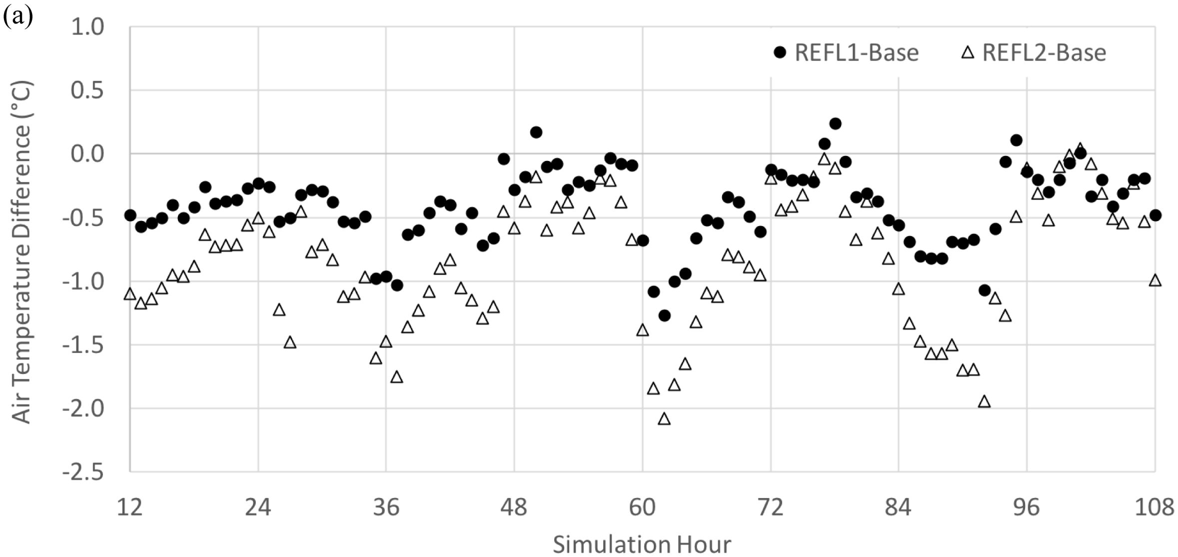
Date	Temperature, Max, °C	Temperature, Min, °C	Average Dewpoint, °C	Air Mass Category
1988-08-01	37.78	25.56	22.22	DT
1988-08-02	37.22	26.67	22.22	DT
1988-08-03	35.56	26.67	21.67	MT+
1988-08-04	35.56	25.56	22.22	MT+
1988-08-05	30.56	18.89	20.00	MT+
1988-08-11	33.33	22.22	22.78	MT+
1988-08-12	33.33	23.89	22.22	MT+
1988-08-13	32.22	25.00	22.78	MT+
1988-08-14	32.78	23.89	23.89	MT+
1988-08-15	33.89	23.89	21.67	MT+
1988-08-16	36.67	23.33	22.78	MT+
1995-07-12	35.56	22.78	21.11	DT
1995-07-13	39.44	27.22	25.00	MT++
1995-07-14	37.78	28.33	25.00	MT++
1995-07-15	36.11	23.89	22.22	MT++
2012-07-02	36.11	22.22	20.56	DT
2012-07-03	38.33	25.00	19.44	DT
2012-07-04	38.33	26.11	20.56	DT
2012-07-05	39.44	26.67	20.56	MT+
2012-07-06	39.44	28.33	21.67	DT

~~**Figure 5. Interannual frequency of DT and MT+ days in Chicago: 1960-2016.**~~

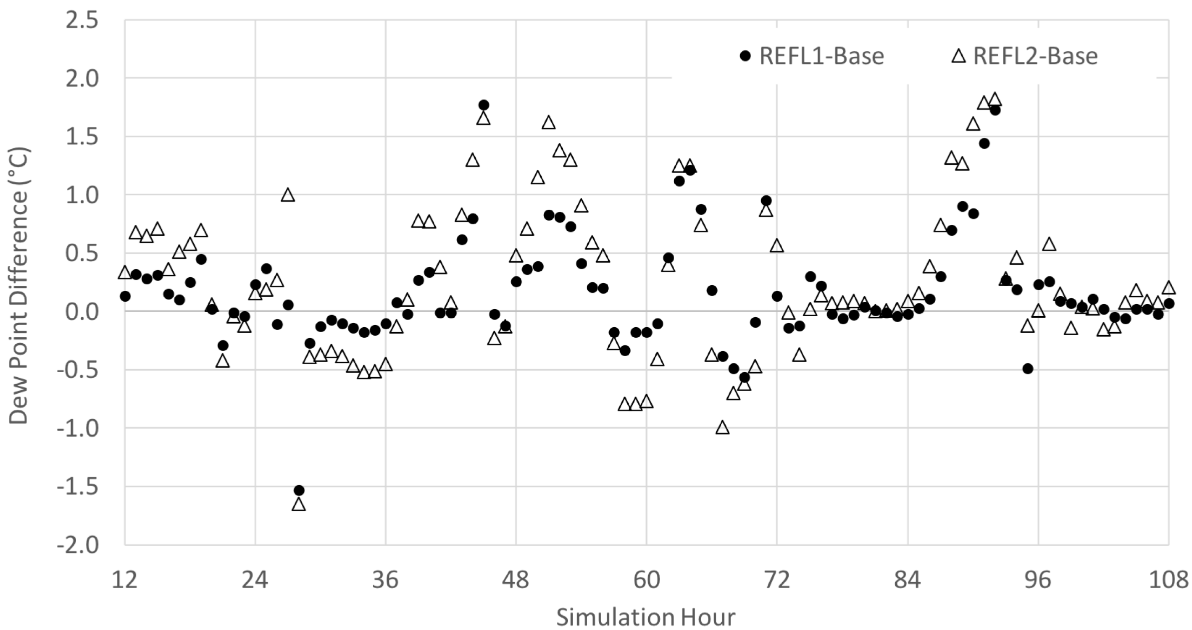
The August 1 - 5, 1988 simulations for REFL1 and REFL2 show temperature daytime reductions similar to those found in the Boston results, averaging from 1.5°C to over 2°C (Figure 4). The pattern is quite regular from one day to the next. The magnitude of these peaks under the REFL2 scenario are much higher than REFL1. Much like the Boston scenarios, there are both decreases and increases in dewpoint temperature, although the number of dewpoint decreases seem greater in Chicago than in Boston. In addition, the dewpoint departures from the baseline are generally smaller than the temperature departures, and they are much less cyclical. The other EHEs behaved rather similarly to the August simulations illustrated here, and dewpoint variations were approximately one third those for temperature.

Figure 4. ~~**Hourly plots of temperature (a) and dewpoint (b) between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Chicago, August 1-5, 1988. Positive values indicate lower simulation values than the baseline (thus, a modeled reduction in values); negative values indicate higher simulation values than the baseline.**~~ **Plots of simulated air temperature (a) and dewpoint temperature (b) differences between the baseline (which represents reality) and REFL1 and REFL2 scenarios for Chicago, for the August 1-5, 1988 (108 hour long) heat wave episode. Negative values indicate lower values for the mitigation cases relative to the baseline (thus, a modeled reduction in values).**

(a)



(b)



~~**Figure 5. The magnitude of temperature reductions in the Chicago area under the REFL2 scenario, August 1, 1988, at 11AM (a) and 3PM (b). Arrows indicate prevailing windspeed and direction.**~~

The air mass change/mortality results for Chicago were more robust than those uncovered for Boston (see Table 8). Eight days demonstrated changes in air mass for the REFL2 scenario; five days showed changes for REFL1. Some of those changes were from the very oppressive DT to the slightly less oppressive MT+, but a few were from an oppressive air mass to a non-oppressive one. For example, during the August 5, 1988 EHE, MT+ was altered to a much less dangerous DM air mass, with an associated large drop in mortality.

Table 8. A summary of results for all four evaluated EHEs in Chicago. Boxes shaded in light gray represent air mass changes.

	Baseline			REFL1			REFL2		
EHE #1	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 1, 1988	39.7	DT	8.7	39.4	MT+	8.5	39.0	MT+	8.2
August 2, 1988	39.6	DT	13.3	39.3	MT+	13	39.1	MT+	12.9
August 3, 1988	37.3	MT+	16.1	37.0	MT+	15.9	36.4	MT+	15.4
August 4, 1988	36.2	MT+	19.9	35.8	MT+	19.6	35.5	MT+	19.3
August 5, 1988	29.3	MT+	19.1	28.7	MT+	18.7	28.1	DM	9
			77.1			**75.7**			**64.8**
EHE #2	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
August 11, 1988	35.6	MT+	5.5	35.1	MT+	5.2	34.8	MT+	4.9
August 12, 1988	35.2	MT+	9.9	34.6	MT+	9.4	34.1	MT+	9
August 13, 1988	31.8	MT+	11.8	31.5	MT+	11.6	31.1	MT+	11.3
August 14, 1988	35.3	MT+	19.2	34.9	MT+	18.9	34.2	MT+	18.3
August 15, 1988	33.0	MT+	22	32.2	MT+	21.4	31.3	MT	11.4
August 16, 1988	37.1	MT+	29.8	36.7	MT+	29.5	36.2	MT+	19.9
			98.2			**96**			**74.8**
EHE #3	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 12, 1995	36.0	DT	5.9	35.5	MT+	5.5	34.9	MT+	5
July 13, 1995	41.2	MT++	14.5	41.2	MT++	14.5	40.6	MT++	14
July 14, 1995	39.6	MT++	17.9	39.9	MT++	18.1	39.6	MT++	17.9
July 15, 1995	35.6	MT++	19.4	35.3	MT+	19.2	34.8	MT+	18.8
			57.7			**57.3**			**55.7**
EHE #4	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality	AT17, °C	Air Mass Type	Excess mortality
July 2, 2012	35.4	DT	5.4	35.4	DT	5.4	34.9	MT+	5
July 3, 2012	34.5	DT	9.3	33.7	MT+	8.7	33.6	MT+	8.6
July 4, 2012	36.7	DT	15.6	36.4	DT	15.4	36.0	DT	15.1
July 5, 2012	29.5	MT+	14.7	28.6	MT+	14	28.6	MT+	14
July 16, 2012	39.7	DT	27.2	40.9	DT	28.1	38.8	DT	26.5
			72.2			**71.6**			**69.2**
TOTAL EXCESS MORTALITY			**305.2**			**300.6**			**264.5**

TOTAL PERCENT REDUCTIONS	**2%**	**13%**

The two August 1988 events showed dramatic drops in excess mortality, particularly under the REFL2 scenario. For example, the early August EHE had an estimated 77 excess deaths under baseline conditions, and this was reduced to about 65 deaths using REFL2 criteria, representing a 16% drop in excess mortality and 12 lives saved. The mid-August MT+ dominated event yielded even better results. One day was shifted to a non-offensive MT air mass; in all, we estimated approximately 24 saved lives, from 98 under baseline conditions to 74 using the REFL2 scenario.

The other two EHEs, including the very dangerous July 1995 EHE, did not demonstrate dramatic drops. The July 2012 REFL2 scenario showed only a 4% drop in mortality from the baseline, or three lives saved. Two days demonstrated air mass changes, but they were from DT to a nearly-as-oppressive MT+. Although the magnitude of the cooling was similar to the two 1988 EHEs, we have found that the dry, hot events often do not demonstrate the life-savings benefits that are gained during hot, humid events. We will explain reasons for this shortly.

Our biggest surprise was the lack of lower mortality response in the most extreme event (July 1995). A problem is immediately apparent: of the four EHEs evaluated here, the estimated number of deaths was lowest for the July 1995 event even though it is well-documented that this was the worst heat wave in recent Chicago history in terms of lives lost. Additionally, our modeling indicates only a 3% decrease in mortality under the REFL2 scenario, which translates to two lives saved.

Excluding the July 1995 EHE, the three remaining EHEs were estimated to have killed about 250 individuals. Chicago averages about one or two of these magnitude events annually, as the majority of years has at least ten DT and MT+ days per summer. Based upon our modeling, the REFL2 scenario would have saved 39 lives during these three events, a 16% reduction in heat-related mortality. If, on average, we can expect a 16% reduction in heat-related deaths during a typical Chicago EHE, this would amount to 150 to 300 lives saved in a decade based upon the number of these events that typically occur.

DISCUSSION

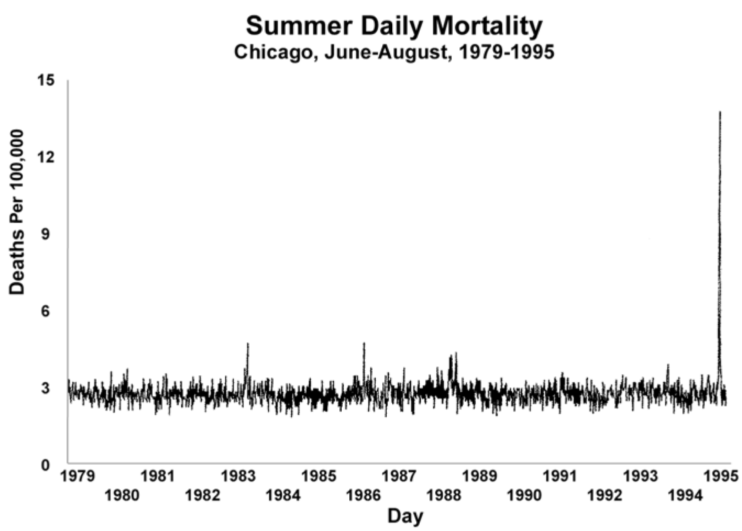
All the EHEs demonstrated cooler temperatures and decreases in mortality under the higher reflectance scenarios. Although the EHEs generally showed similar reductions in temperature under the various REFL scenarios, the REFL2 scenario demonstrated about a two to three times greater reduction than REFL1, and the magnitude of lives saved varied considerably.

We offer two suggestions as to why some EHEs performed better than others. The first involves whether the EHE was hot and humid or hot and dry. In general, the hot and humid events showed more drastic drops in mortality than the hot and dry events, particularly in Chicago. We believe this is because most of the DT days, when cooled by 1°C to 2°C, will change to an MT+ air mass, which is still oppressive and responsible for heat-related mortality. Dewpoint temperatures do not drop as much as air temperatures on most days, and sometimes even increase. Thus, a cooler DT day with a similar dewpoint temperature will switch to an MT+ if there is an air mass change on that day. This leads to minimal reduction in excess mortality on those days, thereby diminishing the health benefits of the increased reflectance. Our best results are often obtained during MT+ dominated EHEs, since air mass changes are never to the oppressive DT, but rather to the much more benign and common MT air mass, or occasionally to a common DM air mass, as was the case on August 5, 1988.

Second, we suggest that the most severe EHE, the Chicago July 1995 event, is not handled well by our models because this EHE is an incredible outlier. ~~Table 9 demonstrates that~~ The temperature reductions during that event were similar to the other EHEs we evaluated. Most of the REFL1 reductions were between 0.5°C to 1.0°C, while most of the REFL2 reductions were 1°C or greater. Most of the reductions were in the late morning or afternoon, much like the other EHEs we evaluated. In addition, the July 1995 EHE was largely a very hot and humid event, which we have indicated should respond in a better fashion in terms of lives saved. So why did this EHE not respond like the others if the temperature reductions were somewhat similar? ~~***Table 9. Temperature reductions during the July 1995 EHE in Chicago. Numbers in orange indicate reductions of greater than 1.5°C and pink numbers show reductions of greater than 2°C.***~~

One reason for this unexpected response relates to the outlier nature of the July 1995 event in terms of lives lost. When evaluating the raw mortality data for Chicago, it is clear that the July 1995 EHE is truly remarkable for the number of lives lost (Figure 5). The average daily summer death rate in Chicago is 3 per 100,000, but on two days during the EHE of July 1995 that number approached 14 per 100,000. The two August 1988 EHEs are also seen in Figure 5; those EHEs, along with any others that stand out, were much smaller in magnitude.

Figure 5. Number of daily all-cause deaths per 100,000 in Chicago: June through August, 1975 – 1995.



When developing our Chicago mortality algorithm for DT and MT+ days, all of the daily mortality totals for these oppressive air masses were included as dependent variables. Although those atypical July 1995 days were included, they had less impact on the algorithm than the dozens of DT and MT+ days that typically had 3.5 to 5 deaths per 100,000. Thus, considering the linear nature of the stepwise multiple regression that we employed, the few highly extreme days of July 1995 had much less impact upon the algorithm than they had in terms of real-life impact. As a result, the Chicago algorithm greatly underestimated the number of excess deaths for those July days in 1995 when the EHE was most extreme. That explains the 57 baseline excess deaths that the algorithm estimated for the July 1995 EHE, which is more than an order of magnitude below the number of actual excess deaths. It also partially explains why there was such a comparatively small drop in mortality using the same algorithm for the REFL1 and

REFL2 scenarios. In short, based on the way our study was modeled we could not properly handle an event such as the July 1995 EHE in Chicago.

An obvious question is why the July 1995 event was, in reality, so anomalous. The weather data do not fully explain why this EHE was so much worse than the others in terms of actual excess mortality. Table 6 above, which compares ATs for all the events, shows that there was a day during the 1995 event that exceeded a 41°C AT, and another day that exceeded 39.5°C. Those are exceedingly hot days, but the August 1 – 5, 1988 EHE had two days that exceeded 39.5°C (although no days during this event exceeded 40°C). The pertinent observation here is that the 1995 EHE was not much worse in terms of AT than the early August 1988 event, but the mortality rate was greater by fivefold. How can that be explained? The non-linear nature of the impact of AT on mortality is one partial explanation; a 1°C or 2°C increase in AT has a considerably greater effect when temperatures are approaching 40°C than when they are 30°C – 35°C . However, our main hypothesis relates to the *timing* of the July 1995 EHE. Figure 55 indictates that there were EHEs in 1983 and 1986 which preceeded the two events we evaluated in August of 1988. The data show there were virtually no excessive heat deaths from the period between 1988 and the EHE of July 1995. Therefore, we believe that the number of vulnerable individuals accumulated during that relatively meteorologically-benign seven-year period led to a highly inflated total for July 1995. Several EHEs in the early and mid-1980s, as seen in Figure 55, killed some of the heat-vulnerable people, leaving less to die during the two August 1988 EHEs.

With the exception of the July 1995 event, we believe our model is a valid approach to evaluate both the meteorological and health impacts of high reflectance solutions to address urban heating.

Conclusion

The goal of this research was to quantify how increasing urban reflectance through the use of reflective roof products can lessen the intensity of EHEs and save lives during such events. We employed an air mass-based synoptic climatological approach to define EHEs in terms of "oppressive air masses," which historically have been associated with excess mortality during EHEs. We also attempted to determine if some days might actually switch to a less oppressive air mass if the reduction in heat was sufficiently large.

The following are our major findings:

- Based on the unique algorithms we developed for each city, we estimate that in an average summer about 70 people die from heat-related causes in Boston and slightly over 100 die in Chicago.
- The algorithms are more reliable for the typical heat events and underestimate mortality significantly for the most extreme event (e.g., July 1995 EHE in Chicago).
- For Boston, the modeling typically demonstrates a significant cooling, particularly during daytime hours. The magnitude of cooling is greatest for the REFL2 scenario, where urban reflectance was increased by 0.25. In some cases, cooling approaches, and even exceeds, 1.5°C using the REFL2 scenario, and is greater than 0.6°C under the REFL1 scenario. Chicago simulations produce similar but slightly larger cooling values, with some exceeding 2°C.

- Dewpoint temperatures show more irregular fluctuations than air temperature for both cities, including some increases under the cooling scenarios. Decreases in dewpoint under the scenarios are more prevalent in Chicago than in Boston.
- All the evaluated EHEs for both cities show reductions in excess heat-related mortality, although the magnitude of the reduction is highly variable from one heat event to the next. For Boston, the average reduction in mortality for all the EHEs using the REFL1 scenario is 8.1%, and is 9.2% for REFL2. This translates to about 12 saved lives for the four events under REFL2 conditions. For Chicago, the REFL2 scenario leads to an average reduction in mortality of over 10%, with one event showing a 24% decline.
- The modeling does a poor job of identifying lives saved during the most intense EHE (July 1995) in Chicago. Since that EHE was an outlier, it should not be assigned to the same mortality-estimating algorithm as the other three EHEs. Nevertheless, the results for the other EHEs in Chicago were intuitive, and we estimate that under the REFL2 scenario 39 lives would have been saved. This could translate to approximately 200-300 saved lives a year during a decade's worth of EHEs in Chicago.
- The model projects larger numbers of saved lives occurring during hot and humid heat events for both cities as compared to hot and dry events.
- We suggest that more extensive use of reflective roofs in these two major cities would contribute significantly to saving numerous lives from heat during oppressive weather days.

There are several avenues that should be pursued to improve and expand upon the results of this study. The first would be a means to handle the most excessive of heat events, such as the Chicago July 1995 EHE. We concluded that this event was not evaluated properly when lumped together with the other three Chicago EHEs, since excess deaths were close to an order of magnitude higher during the 1995 EHE. We believe that a lack of severe heat for several years prior to the 1995 EHE partially contributed to its extreme mortality response, since it was only slightly hotter and more oppressive than the 1988 and 2012 events in terms of meteorology. There were obviously other factors at play as well, which need to be identified precisely.

The scope of our work was limited to heat-related mortality only; we did not evaluate morbidity, such as emergency room visits and ambulance calls. There is now increasing research on emergency room admissions and ambulance calls during EHEs (e.g., [28]), and there is no doubt that a study like this can be expanded to include morbidity, which is more widespread during EHEs than mortality. In addition, this study did not attempt to evaluate the potential impacts of human-induced climate change, and it is feasible to expect that more intense utilization of reflective technologies will help mitigate or delay these negative meteorological impacts upon human health.

We hope to expand our work in Boston and Chicago to evaluate more directly the impacts of cool technologies upon the suburban ring, which continues to become more densely populated in both of these urban areas. Thus, an even more comprehensive evaluation of the benefits of reflective roofing materials and other cool cities solutions is a longer-term goal growing out of this evaluation.

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References

[1] United Nations, Department of Economic and Social Affairs, Population Division. "World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)," United Nations, 2014, p. 1, http://web.archive.org/web/20181128224032/https://esa.un.org/unpd/wup/publications/files/wup2014-highlights.pdf

[2] McCarthy, M., Best, M., and Betts, R., "Climate Change in Cities Due to Global Warming and Urban Effects," *Geophysical Research Letters,* Vol. 37, No. 9, 2010, http://dx.doi.org/10.1029/2010GL042845

[3] Hibbard, K., Hoffman, F., Huntzinger, D.N., and West, T., "Changes in Land Cover and Terrestrial Biogeochemistry," *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, U.S. Global Change Research Program, Washington, DC, USA, 2017, pp. 277–302, http://dx.doi.org/10.7930/J0416V6X

[4] Vanos, J., Kalkstein, L., and Sanford, T., "Detecting Synoptic Warming Trends Across the U.S. Midwest and Implications to Human Health and Heat-Related Mortality," *International Journal of Climatology,* Vol. 35, No. 1, 2015, pp. 85–96, http://dx.doi.org/10.1002/joc.3964

[5] Harvard Medical School, Center for Health and the Global Environment, "Climate Change Futures: Health, Ecological, and Economic Dimensions," Harvard Medical School, Boston, MA, 2005, pp. 57–58, http://web.archive.org/web/20181128213652/http://www.eird.org/isdr-biblio/PDF/Climate%20change%20futures.pdf

[6] Steadman, R., "A Universal Scale of Apparent Temperature," *Journal of Climate and Applied Meteorology,* Vol. 23, No. 12, 1984, pp. 1674–87, http:/dx.doi.org/10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2

[7] Heaviside, C., Macintyre, H., and Vardoulakis, S, "The Urban Heat Island: Implications for Health in a Changing Environment," *Current Environmental Health Reports,* Vol. 4, No. 3, 2017, pp. 296–305, http://dx.doi.org/10.1007/s40572-017-0150-3

[8] Basu, R., "High Ambient Temperature and Mortality: A Review of Epidemiologic Studies from 2001 to 2008," *Environmental Health,* Vol. 8, No. 1, 2009, http://dx.doi.org/10.1186/1476-069X-8-40

[9] Stone Jr., B., Vargo, J., Liu, P., Habeeb, D., DeLucia, A., Trail, M., Hu, Y., Russell, A., "Avoided Heat-Related Mortality Through Climate Adaptation Strategies in Three U.S. Cities," *PLoS One,* Vol. 9, No. 6, 2014, http://dx.doi.org/10.1371/journal.pone.0100852

[10] Santamouris, M., "Cooling the Cities–A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments," *Solar Energy,* Vol. 103, 2014, pp. 682–703, http://dx.doi.org/10.1016/j.solener.2012.07.003

[11] Li, D., Bou-Zeid, E., and Oppenheimer, M., "The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies," *Environmental Research Letters,* Vol. 9, No. 5, 2014, http://dx.doi.org/10.1088/1748-9326/9/5/055002

[12] Campra, P., "Global and Local Effect of Increasing Land Surface Reflectance as a Geo-Engineering Adaptation/Mitigation Option: A Study Case of Mediterranean Greenhouse Farming," Climate Change-Research and Technology for Adaptation and Mitigation, 2011, http://dx.doi.org/10.5772/23286

[13] Dixon, P.G., Allen, M., Gosling, S., Hondula, D., Ingole, V., Lucas, R., and Vanos, J., "Perspectives on Synoptic Climate Classification and Its Role in Interdisciplinary Research," *Geography Compass,* Vol. 10, No. 4, 2016, pp. 147–164, http://dx.doi.org/10.1111/gec3.12264

[14] Hondula, D., Vanos, J., and Gosling, S., "The SSC: A Decade of Climate-Health Research and Future Directions," *International Journal of Biometeorology*, Vol. 58, No. 2, 2013, pp. 109–120, http://dx.doi.org/10.1007/s00484-012-0619-6

[15] Sheridan, S., "The Redevelopment of a Weather-Type Classification Scheme for North America," *International Journal of Climatology,* Vol. 22, No. 1, 2002, pp. 51–68, http://dx.doi.org/10.1002/joc.709

[16] Sheridan, S., Kalkstein, L., "Progress in Heat Watch-Warning System Technology," *Bulletin of the American Meteorological Society,* Vol. 85, No. 12, 2004, pp. 1931–41, http://dx.doi.org/10.1175/BAMS-85-12-1931

[17] Lee, D.G., Kim, K.R., Kim, J., Kim, B.J., Cho, C.H., Sheridan, S., Kalkstein, L., Kim, H., and Yi, S.M., "Effects of Heat Waves on Daily Excess Mortality in 14 Korean Cities During the Past 20 Years (1991-2010): An Application of the Spatial Synoptic Approach," *International Journal of Biometeorology,* Vol. 62, No. 4, 2018, pp. 575–583, http://dx.doi.org/10.1007/s00484-017-1466-2

[18] Tan, J., Zheng, Y., Song, G., Kalkstein, L., Kalkstein, A., and Tang, X., "Heat Wave Impacts on Mortality in Shanghai: 1998 to 2003," *International Journal of Biometeorology,* Vol. 51, No. 3, 2007, pp. 193–200, http://dx.doi.org/10.1007/s00484-006-0058-3

[19] Greene, S., Kalkstein, L., Mills, D., and Samenow, J., "An Examination of Climate Change on Extreme Heat Events and Climate-Mortality Relationships in Large U.S. Cities," *Weather, Climate, and Society,* Vol. 3, No. 4, 2011, pp. 281–292, http://dx.doi.org/10.1175/WCAS-D-11-00055.1

[20] Kalkstein, L., Sailor, D., Shickman, K., Sheridan, S., and Vanos, J., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia," District Department of the Environment, Department of Consumer and Regularatory Affairs, 2013, 28p., http://web.archive.org/web/20181128225853/https://www.coolrooftoolkit.org/wp-content/uploads/2013/10/DC-Heat-Mortality-Study-for-DDOE-FINAL.pdf

[21] Sheridan, S., "Spatial Synoptic Classification Homepage," Department of Geography, Kent State University, 2018, http://web.archive.org/save/http://sheridan.geog.kent.edu/ssc.html (accessed 28 Sept. 2018).

[22] National Center for Health Statistics, "National Vital Statistics System," Centers for Disease Control and Prevention, 2018, http://web.archive.org/web/20181127154514/https://www.cdc.gov/nchs/nvss/deaths.htm (accessed 27 Nov. 2018).

[23] Sheridan, S., Kalkstein, A., and Kalkstein, L., "Trends in Heat-Related Mortality in the United States, 1975-2004," *Natural Hazards,* Vol. 50, No. 1, 2009, pp. 149-60, http://dx.doi.org/10.1007/s11069-008-9327-2

[24] Kalkstein, L., Greene, J., Kim, K.R., Choi, Y.J., and Lee, D.G., "The Application of the European Heat Wave of 2003 to Korean Cities to Analyze Impacts on Heat-Related Mortality," *International Journal of Biometeorology,* Vol. 60, No. 2, 2016, pp. 231–242, http://dx.doi.org/10.1007/s00484-015-1020-z

[25] Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C.S.B., Grossman-Clarke, S., Loridan, T., Manning, K., Martilli, A., Miao, S., Sailor, D., Salamanca, F.P., Taha, H., Tewari, M., Wang, X., Wyszogrodzki, A.A., and Zhang, C., "The Integrated WRF/Urban Modeling System: Development, Evaluation, and Applications to Urban Environmental Problems," *International Journal of Climatology*, Vol. 31, No. 2, 2011, pp. 273–288, http://dx.doi.org/10.1002/joc.2158

[26] Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., "Completion of the 2011 National Land Cover Database for the Conterminous United States: Representing a Decade of Land Cover Change Information," *Photogrammetric Engineering and Remote Sensing*, Vol. 81, No. 5, 2015, pp. 345–354, http://dx.doi.org/10.14358/PERS.81.5.345

[27] Klinenberg, E., *Heat Wave: A Social Autopsy of Disaster in Chicago,* University of Chicago Press, Chicago, IL, 2002, 305p.

[28] Davis, R., and Novicoff, W., "The Impact of Heat Waves on Emergency Department Admissions in Charlottesville, Virginia, U.S.A.," *International Journal of Environmental Research and Public Health,* Vol. 15, No. 7, 2018, p. 1436, http://dx.doi.org/10.3390/ijerph15071436