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Climate change, heat waves, and mortality projections for Chicago

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ABSTRACT

Over the coming century, climate change is projected to increase both mean and extreme temperatures as heat waves become more frequent, intense, and long-lived. The city of Chicago has already experienced a number of severe heat waves, with a 1995 event estimated to be responsible for nearly 800 deaths. Here, future projections under SRES higher (A1FI) and lower (B1) emission scenarios are used to estimate the frequency of 1995-like heat wave events in terms of both meteorological characteristics and impacts on heat-related mortality. Before end of century, 1995-like heat waves could occur every other year on average under lower emissions and as frequently as three times per year under higher. Annual average mortality rates are projected to equal those of 1995 under lower emissions and reach twice 1995 levels under higher. An "analog city" analysis, transposing the weather conditions from the European Heat Wave of 2003 (responsible for 70,000 deaths across Europe) to the city of Chicago, estimates that if a similar heat wave were to occur over Chicago, more than ten times the annual average number of heat-related deaths could occur in just a few weeks. Climate projections indicate that an EHW-type heat wave could occur in Chicago by mid-century. Between mid- and end-of-century, there could be as many as five such events under lower, and twenty-five under higher emissions. These results highlight the importance of both preventive mitigation and responsive adaptation strategies in reducing the vulnerability of Chicago's population to climate change-induced increases in extreme heat.

Introduction

Extreme heat and oppressive heat events are known to produce elevated rates of both illness and death due to heat stress (Martens, 1998; McGeehin and Mirabelli, 2001; Schär et al., 2004). In addition to their direct impacts, sustained extreme heat events exacerbate preexisting cardiovascular, respiratory, and other conditions (Ellis and Nelson, 1978; Kalkstein and Valimont, 1987).

A direct effect of rising temperatures is an increase in the frequency and severity of extreme heat and heat wave events. As climate changes, very hot days and heat wave events are projected to become more frequent and severe (Tebaldi et al., 2006). At the same time, the risk of severe, prolonged heat wave events, such as those that occurred over Chicago in 1995 and Europe in 2003, is also increasing (Meehl and Tebaldi, 2004; Stott et al., 2004).

Excessive heat is currently the leading cause of weather-related deaths across the United States (NCDC, 2004). During the summer of 1980, as many as 10,000 deaths in the United States may have been associated with oppressive heat (NCDC, 2004). Although some research has suggested an overall decrease in heat vulnerability in recent decades (Davis et al., 2002), especially as air conditioning has become more commonplace (Smoyer, 1998), there is still a clear vulnerability to heat, and dramatic mortality episodes have occurred in the United States within the last 10 years (Klinenberg, 2002). One recent study indicates that, following a decline from the 1970s to the early 1990s, heat vulnerability has remained relatively constant since and may even be increasing in some cities (Sheridan et al., 2008).

In recent decades, two well-documented heat wave events have centered over major cities: Chicago in 1995 and Paris in 2003. Much can be learned regarding the potential impact of climate change on extreme heat and heat-related health concerns for the city of Chicago by examining the meteorological conditions leading to these events and their impact on urban mortality and morbidity rates.

Mortality and morbidity during the 1995 Chicago heat wave

In July of 1995, the city of Chicago experienced a heat wave unprecedented in its 123-year-old weather records (Livezey and Tinker, 1996). Maximum daily temperatures were equal to or greater

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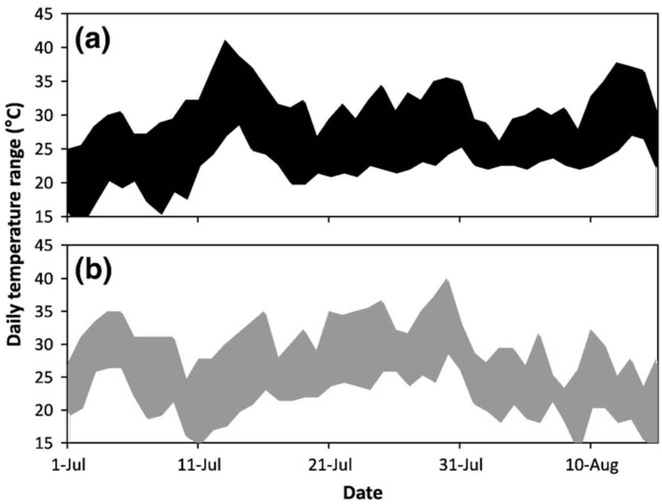

Fig. 1. Range of observed daily temperatures from July 1st to August 15th at Chicago Midway for the heat wave summers of (a) 1995 (black) and (b) 1999 (gray) (in °C). Peak heat wave days were July 13–14 in 1995 and July 29–30 in 1999.

than 32 °C (90 °F) for seven consecutive days and greater than 38 °C (100 °F) for 2 days at the peak of the heat wave (Fig. 1a). Even more importantly, there was no relief at night, as nighttime minimum temperatures were over 27 °C (80 °F) during the hottest days.

During the 1995 heat wave, 739 "excess" deaths were recorded (Semenza et al., 1999). Initially, 514 of these were classified as heat-related (Whitman et al., 1997), but a recent reanalysis estimates a greater total of 697 heat-related deaths during the 1995 heat wave (Kaiser et al., 2007). Although some deaths may have merely been anticipated by a few days to weeks, Semenza et al. (1999) estimated that only 26% of deaths were due to this type of displacement or "harvesting," leaving over 500 deaths directly attributable to the heat wave event. Even this number may be an underestimate, as Shen et al. Q2 (1998) found that excess mortality rates during the Chicago heat wave were higher than the estimated heat-related mortality (24–26 per 100,000 as opposed to 19 per 100,000), likely due to an overly narrow classification of heat-related death.

During the 1995 heat wave, there were also more than 3000 excess emergency department visits (Dematte et al., 1998), and more than 1000 hospital admissions as compared to what would normally be expected at that time of the year (Semenza et al., 1999). Most hospital admissions were due to dehydration, heat stroke, and heat exhaustion among people with underlying medical conditions. Of those admitted with heat stroke, 21% died in hospital and 28% during the following year (Dematte et al., 1998).

The effects of the heat wave were likely enhanced by micro-meteorological effects such as the urban heat island (leading to higher temperatures at weather observing stations closer to the center of Chicago, and lower temperatures at suburban sites), and the fact that the moderating effect of the lake was minimized by the southerly winds prevailing during the heat wave, which virtually eliminated the cooling effect of lake breezes. At the same time, socio-economic factors also enhanced the risk of heat-related health impacts. Changnon et al. (1996) highlight several of these, including an inadequate heat wave warning system, power failures, inadequate ambulance service and hospital facilities, an aging population, and improper ventilation due to lack of resources (i.e., residents who were unable to afford air conditioning). For some neighborhoods, risk factors even included the fact that people were afraid to open their windows due to crime.

Further analyses focus on statistical correlations of risk factors with mortality, ranking the different risk factors. The results emphasize the importance of access to air conditioning (O'Neill et al., 2005; Naughton et al., 2002) and vulnerability due to existing medical conditions and/or social isolation (Semenza et al., 1996; Naughton et al., 2002). Age, race, and social class were also contributing factors. For people ages 65 years and up, hospital admissions were up by 35% during the heat wave, as opposed to an increase of 11% for the general population; mortality rates for that age group were also higher (Whitman et al., 1997; Semenza et al., 1999). In terms of race, heat-related deaths were disproportionately larger in the black community and smaller in the Hispanic community, as compared to the Chicago-wide average (Whitman et al., 1997; Semenza et al., 1999). Independent of race, the relative affluence levels of neighborhoods were also a mitigating factor, with wealthier and more commercially successful areas showing lower mortality rates, likely because more of their inhabitants were better able to afford central air conditioning (Browning et al., 2006; O'Neill et al., 2005).

Many of the lessons learned during the 1995 heat wave have already been acted on. A second heat wave in 1999, just slightly less severe than the 1995 event (Fig. 1b), resulted in only 114 excess deaths attributed to heat (Palecki et al., 2001). Furthermore, more than half the deaths were for people less than 65 years old, suggesting that adaptation strategies focused on the elderly population were succeeding (Naughton et al., 2002). Despite these successes, however, future climate changes may challenge even currently successful adaptation strategies. Whether this is likely to be the case is the first question we investigate here, by assessing the projected frequency of 1995-like heat wave events for the 21st century: first, in terms of their meteorological characteristics, and second, in terms of their mortality characteristics.

Mortality and morbidity during the 2003 European heat wave

During the summer of 2003, western Europe was impacted by a heat wave of historic proportions (Trigo et al., 2005). For most of that summer, temperatures were well above average across a broad region extending from the British Isles to the Iberian Peninsula and eastward to Germany and Italy. The most extreme conditions centered in France where in Paris, maximum temperatures equaled or exceeded 38 °C (100 °F) for 6 days, and the heat broke long-standing maximum and minimum temperature records during August 3–13 (Planton et al., 2004). The temporal extent of this heat wave event was also unprecedented. For June 1 through August 31, 2003, maximum temperatures were above average for all but 8 days in Paris and, for at least half of those days, average maximum temperatures were exceeded by 6 °C (10 °F) or more (Fig. 2a). Minimum daily temperatures were also abnormally high. Electricity demand rose by more than 4%, exacerbating concerns regarding the ability to cool both nuclear and fossil fuel power plants (Salagnac, 2007).

Initial estimates of the death toll incurred by the European Heat Wave (EHW) of 2003 centered around 30,000 (UNEP, 2004). This estimate was first revised upward by Valleron and Boumendil (2004) to over 40,000 deaths. More recently, an analysis by Robine et al. (2008) identified a total of 70,000 excess deaths in 16 European countries during the summer of 2003. This latest estimate was based on excess mortality rates rather than recorded heat-related deaths, again highlighting the potential for heat-related mortality to be underestimated through individual death counts.

Estimates vary regarding the magnitude of the harvesting effect of the EHW, whether some of the estimated 70,000 deaths were merely anticipated by a period of days to months. However, most agree that this effect was relatively small for this event. Robine et al. (2008) find no harvesting effects at all in their estimates of 70,000 excess deaths in 16 countries during the summer of 2003. A modest harvesting effect, amounting to about one-third of total deaths in France, is estimated by Toulemon and Barbieri (2008).

Analysis of the 2003 EHW indicates that its duration and magnitude is beyond that of any similar event that has occurred in the United States or Europe over the last 150 years. During the EHW,

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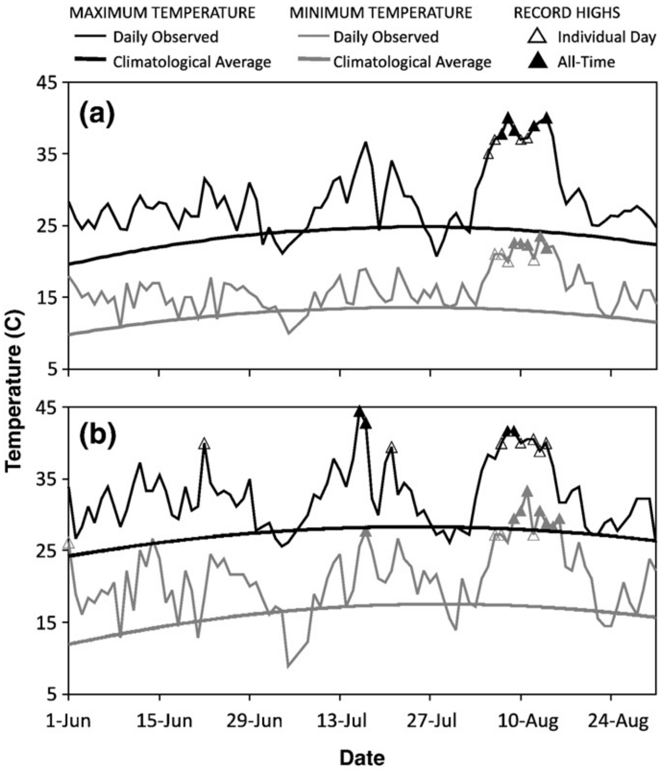

Fig. 2. Daily observed and long-term climatological average maximum and minimum temperatures for (a) Paris during 2003 summer and (b) Chicago during a 2003-analog summer (in °C). Days marked with open triangles exceed the historical maximum and/or minimum temperature record for that day; days with solid triangles exceed the all-time August record.

for example, the city of Paris reported 2600 excess emergency room visits, 1900 excess hospital admissions, and 475 excess deaths (Dhainaut et al., 2004).

As with Chicago, a number of factors have been identified that rendered certain segments of the European population more at risk or vulnerable to extreme heat both during and after the heat wave event. For example, nearly two-thirds of all excess deaths were female; also, a disproportionately large amount of deaths were experienced by age groups over 65 years, with excess deaths increasing by as much as 27% for people over the age of 85 years (Robine et al., 2008) and for those at home or in retirement institutions, as compared to hospitals (Fouillet et al., 2006). Case studies in Germany and France quantified the contribution of elevated ozone levels to increased risk and identified respiratory disease as being most strongly correlated with extreme heat (Hoffmann et al., 2008; Filleul et al., 2006). Not unrelated, populations in urban areas showed the greatest sensitivity to the extreme heat (Salagnac, 2007).

Following the EHW, Lagadec and Laroche (2005) highlighted a number of contributing risk factors, including the absence of alert systems to inform the population of the heat risk, and other preventative measures that could have been taken by the public heath sector. As with Chicago, again, the response of the public health authorities – at least in France – appears to have borne fruit. Actual mortality for a heat wave event in 2006 was two-thirds lower than predictions based on historical mortality rates that included the EHW (Fouillet et al., 2008). This suggests that, overall, increased awareness and adaptation measures may have decreased the vulnerability of the French population to extreme heat.

It is clear that adaptation capacities differ significantly between European and North American cities – both in the behavior of their inhabitants and as in the built environment. The importance of air conditioning (particularly central air as opposed to window units) in determining the vulnerability of Chicago's population to extreme heat has already been highlighted by O'Neill et al. (2005) and Naughton et al. (2002) for Chicago, as well as by Salagnac (2007) for France. In fact, recent work has shown that the death rates in five major US cities would have been considerably lower than the number encountered in Europe had a heat wave of the same magnitude as the 2003 EHW occurred on this side of the Atlantic. Both increased air conditioning availability and differing urban structures (less green space and more concrete per unit area in many European cities) can account for most of this difference (Kalkstein et al., 2008).

Nonetheless, a heat wave comparable to the EHW in duration and intensity has yet to occur over North America. Moreover, there is a well-documented pattern of increased mortality in US cities as a result of extreme heat waves (e.g., St. Louis, 1966, 1980, 2006; New York, 1975, 1984, 2006; Philadelphia, 1991, 1993; Chicago, 1995, 1999). This raises the question of what the health impacts of a similar event would be for Chicago. This is the second question we investigate here – first, projecting the meteorological conditions of the EHW over Chicago to estimate projected mortality rates, and then calculating the future probability of such an event in terms of its impact on heat-related mortality.

Description of this analysis

This analysis is part of a larger study examining the potential impacts of climate change on the US Great Lakes and Midwest regions in general, and the city of Chicago in particular. Given Chicago's history of high-impact heat waves and large urban population, this analysis focuses on that city. At the same time, these results are likely to be qualitatively relevant to other large urban centers within the Great Lakes watershed whose populations have demonstrated sensitivity to extreme heat, including Toronto, Minneapolis, and Detroit (Dolney and Sheridan, 2005; O'Neill et al., 2005; Schuman et al., 1964). Specifically, we draw on a large existing body of literature that documents the characteristics and effects of extreme heat in general on urban populations, and two individual heat wave events in particular – the Chicago heat wave of 1995 and the European heat wave of 2003 – to assess the projected impacts of climate change on public health in Chicago. We do so using four complementary analysis methods.

First, we calculate the projected frequency of 1995-like heat wave events in the future, in terms of their meteorological characteristics. This heat wave is the most extreme event in recent memory, and thus serves as an easily recognizable indicator to Chicago's population of a future such event.

At the same time, however, Chicago has already demonstrated the ability to dramatically increase its resilience. Comparing mortality rates for similar heat waves in 1995 and 1999 showed a reduction of nearly four-fifths over that time (Palecki et al., 2001). For that reason, we also estimate projected changes in the frequency and intensity of offensive air mass events associated with elevated heat-related mortality, in order to generate projections of increases in year-to-year mortality that *include* adaptation. In this way, we attempt to estimate the frequency of future summers with mortality rates, rather than merely meteorological conditions, similar to those of 1995. We hypothesize that, given the already demonstrated potential of city inhabitants to adapt to extreme heat conditions, the number of summers with 1995-like mortality is likely to be significantly less than the number of summers with 1995-like extreme heat.

Third, we use a novel "analog city" approach developed by Kalkstein et al. (2008) to superimpose the meteorological conditions in Paris during the EHW event on the city of Chicago. All other conditions in Chicago remain the same as observed for that city, including its demographics, vulnerability, and infrastructure. We estimate the likely impacts of an EHW-like heat wave on the city today, given its current risk factors. We hypothesize that mortality rates are likely to be lower than those experienced by Paris as the

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population of Chicago is likely to be less vulnerable to extreme heat than that of Paris; at the same time, however, Chicago's mortality rates are likely to be significantly higher than average due to the unprecedented intensity and duration of the heat wave event.

Finally, we use the meteorological characteristics of the EHW to estimate the likely timing of such an event occurring over Chicago, and the frequency of an EHW event by mid- and end-of-century under higher and lower scenarios of future climate change. Throughout the analysis, whenever possible, we deliberately distinguish between the impacts expected under a higher vs. a lower future emissions scenario. Our intention is to highlight the importance of mitigation in limiting future change, as well as the need for adaptation even under a lower emissions scenario.

Observations, climate projections, and methods to estimate heat-related mortality

Climate projections for estimating future heat wave conditions and mortality rates

Hourly and daily weather observations for the Chicago Midway Airport weather station were used to derive the historical characteristics of extreme heat and offensive air mass events in Chicago. The Midway station was selected from eight long-term weather stations in and around Chicago as it is the closest NWS weather station to the majority of Chicago's urban population with both daily and hourly records of temperature and humidity, and daily records of wind direction and speed, sea level pressure, and cloudiness that extend to the present day. Simulations by three global coupled atmosphere-ocean general circulation models (AOGCMs) were used to generate future projections: GFDL CM2.1, HadCM3, and PCM (Delworth et al., 2006; Pope et al., 2000; Washington et al., 2000). Further descriptions of the data and models are provided in Hayhoe et al. (this volume).

Historical AOGCM simulations are based on the standard 20C3M scenario, which represents the best available estimates of 20th-century total (anthropogenic + natural) forcing. The 20C3M scenario includes observed historical emissions of carbon dioxide, methane, and other greenhouse gases; sulfate aerosols, soot, and other particulates; and other radiatively active species produced by human activities such as nitrogen oxides and carbon monoxide. The historical scenario also includes observed changes in solar output and emissions from natural sources such as volcanoes, wetlands, and soils.

Future AOGCM simulations (2000–2099) are based on the IPCC Special Report on Emission Scenarios (SRES; Nakićenović et al., 2000) higher (A1FI) and lower (B1) emissions scenarios. These scenarios use projected future changes in population, demographics, technology, international trade, and other socio-economic factors to estimate corresponding emissions of greenhouse gases and other radiatively active species. Although the SRES scenarios do not include any explicit policies aimed at reducing greenhouse gas emissions to mitigate climate change, the B1 scenario can be seen as proxy for stabilizing atmospheric CO_2 concentrations at or above 550 ppm, as levels reach this value by 2100. Atmospheric CO_2 concentrations for the higher A1FI scenario are 970 ppm by 2100. Input from these scenarios used to drive the future AOGCM simulations include regional changes in emissions of greenhouse gases, particulates, and reactive species.

Variables required for characterizing offensive air mass types and heat wave conditions include daily maximum and minimum temperature, dew point, wind speed and direction, sea level pressure, and cloudiness. Daily temperature and precipitation were statistically downscaled to the Chicago Midway weather station using a statistical asynchronous regression technique described by Dettinger et al. (2004) and Hayhoe et al. (2004). Daily values for temperature and relative humidity for the Chicago Midway weather station were then interpolated to provide 6-hour instantaneous values for each day from 1960 to 2099. These interpolations were based on projected maximum and minimum temperature values and the observed daily cycle in temperature and humidity at that location. Estimates of changes in sea level pressure and cloudiness (in terms of percentage cover) were derived from the AOGCM output fields. Owing to the difficulty in simulating the urban influence on wind speed and direction based solely on changes in large-scale circulation patterns such as those simulated at the scale of a typical AOGCM, climatological wind fields only were used.

Mortality rates and meteorological conditions

Mortality data for the entire United States are available in digital format since 1975. These data include date and cause of death, and the county in which the deceased had passed away. They are derived from files at the National Center for Health Statistics (NCHS, 2000) and are standardized to remove as much variation on mortality as possible that is related to non-meteorological causes, such as trends in population during the period of evaluation. Total deaths per day are evaluated in this analysis, as this has been shown to be superior to subdividing deaths into individual causes (Ebi et al., 2004).

Estimates of changes in average annual heat-related mortality can be determined by developing projections of threshold meteorological conditions beyond which mean mortality has been observed to display a statistically significant increase. Estimates do not account for changes in population, but are rather presented as mortality rates per 100,000. Similarly, they do not account for changes in demographic structure. Coupling the observed elevated risk for people over the age of 65 years with the likely future increase in the proportion of higher demographic levels in the future means that this approach may in fact underestimate the vulnerability of future population to extreme heat and oppressive air mass events. On the other side, however, these estimates also have the potential to be significantly reduced through the success of adaptation techniques to reduce mortality rates, as already suggested through the reduced mortality rates for the >65-year-old age group during the 1999 heat wave as compared to 1995 (Naughton et al., 2002).

The Spatial Synoptic Classification method: Quantifying the meteorological and seasonal contributions to historical heat-related mortality in Chicago

A large body of literature suggests that, rather than responding in isolation to individual weather elements, human health is affected by the interactions from a much larger suite of meteorological conditions that constitute an "offensive air mass" (Kalkstein et al., 1996; Sheridan and Kalkstein, 2004). To estimate future changes in heat-related mortality, therefore, we first classify historical observed daily weather conditions according to the holistic Spatial Synoptic Classification (SSC) air mass (Sheridan, 2002).

For Chicago, two "oppressive" air mass types, Dry Tropical (DT) and Moist Tropical Plus (MT+), have been primarily associated with increased mortality in the past, although some mortality can also occur under warmer conditions with other air masses. In particular, the MT+ air mass is characterized by hot and humid conditions with high overnight temperatures – exactly the conditions during the 1995 and 1999 heat wave events.

Variations of standardized mortality within oppressive air masses are then assessed by developing an algorithm that relates mortality to apparent temperature and time of season. These algorithms include environmental factors that explain the variability in mortality during oppressive weather. Both meteorological (maximum and minimum air temperature, maximum and minimum apparent temperature and dew point, cloud cover, wind speed and direction, and sea level pressure) as well as non-meteorological (consecutive days of oppressive weather, time of season when oppressive weather occurs) factors were potential independent variables within this algorithm.

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The derived algorithms relating heat-related mortality in Chicago to meteorological and seasonal factors, based on historical observed weather conditions and mortality rates, are as follows:

If day is classified as DT or MT+,

$$\text{MORT} = -26.74 + 4.62\,\text{DIS} + 0.777\,\text{AT} \quad (1)$$

If day is classified as another air mass,

$$\text{MORT} = -7.8 + 0.266\,\text{AT} \quad (2)$$

where MORT = anomalous mortality, AT is the apparent temperature (°C) at 5 pm, and DIS is the day's position in a sequence of consecutive days characterized by DT or MT+ air masses. The latter suggests that the longer the offensive air mass persists, the deadlier it becomes.

Previous research for other cities has shown a statistically significant decrease in sensitivity as the population acclimatizes over the course of the summer, but for Chicago's population. this is not significant. In other words, based on the historical record, Chicago's population does not appear to acclimatize to extreme heat over the course of a summer.

The analog European heat wave transposition method

To develop analogs to the 2003 EHW event and calculate the potential excess mortality if such an event were to occur over Chicago, we use the air mass-based meteorological method of Kalkstein et al. (2008). The analog heat wave for Chicago is designed to capture the actual weather conditions of the 2003 EHW, but with the present-day population and infrastructure characteristics of Chicago. This approach does *not* assume that the characteristics of Chicago that make its population vulnerable to the effects of extreme heat resemble those of Paris in any way. Instead, this analog method merely superimposes the weather conditions of the 2003 EHW on Chicago, while all other variables such as population, demographics, infrastructure, and adaptation which determine the likely response of the population to the heat wave are those of Chicago itself. The purpose of the analog city analysis is to show what might happen in Chicago if it experienced a heat wave of the same magnitude as the 2003 EHW event.

To capture the meteorological characteristics of the 2003 EHW, we first calculate the daily deviations from long-term averages for key meteorological variables in Paris that occurred during the EHW. Following Kalkstein et al. (2008), deviations are expressed as a multiple of the standard deviation for each variable's long-term average. Relevant meteorological variables include 6-hour temperature, dew point, cloud cover, sea level pressure, and daily temperature range. The statistical characteristics of the heat wave in Paris are then transferred to Chicago by multiplying Chicago's average summer climatology by the corresponding standard deviation for each variable as occurred in Paris, to produce analog meteorological variables. For example, if on June 1, 2003, Paris' temperature at 6 a.m. were 2.0 standard deviations above the day's average, then Chicago would have a 6 a.m. temperature for that day that was 2.0 standard deviations above its own average. This process was repeated for each day and each of the meteorological variables, such that a complete set of meteorological conditions analogous to Paris 2003 was developed for Chicago (Fig. 2).

Using the analog daily data for Chicago, we next developed an air mass calendar using the identical approach as used in the heat-related mortality calculations above, as described by Sheridan and Kalkstein (2004). Excess mortality was calculated using the Chicago-specific air mass algorithm given previously in Eq. (1). In this way, the characteristics of Chicago that differ from those in Paris (such as its population, demographics, air conditioning use, and other factors affecting heat-related mortality rates) are taken into consideration (Kalkstein et al., 2008).

Climate change impacts on Chicago extreme heat and heat-related mortality

Projected changes in the frequency of heat wave events for Chicago

Over the coming century, climate change is expected to increase not only average summer temperatures but also the frequency of extreme heat associated with heat wave events. Furthermore, climate model simulations indicate that the atmospheric circulation patterns associated with both the severe 1995 heat waves in Chicago as well as the Paris heat wave in 2003 are expected to become more intense, more frequent, and longer-lasting in the second half of the 21st century (Meehl and Tebaldi, 2004).

Here, we investigate the potential impacts of climate change on heat wave frequencies over Chicago by defining a type of heat wave event specific to Chicagoans: the 1995 Chicago heat wave. This is characterized by at least 7 consecutive days with maximum daily temperatures greater than 32 °C (90 °F) and nighttime minimum temperatures greater than 21 °C (70 °F), with daytime maximum temperatures over 38 °C (100 °F) and nighttime temperatures that remained above 27 °C (80 °F) for at least two of those days (Fig. 1a).

It has already been shown by Vavrus and Vandorn (this volume), using the NWS standard heat wave definition of three or more consecutive days with maximum temperatures greater than 32 °C (90 °F), that future heat waves in Chicago are projected to become more frequent, intense, and long-lived. Specifically, the length of future NWS-type heat waves is expected to increase from its present-day average of 3 consecutive days by approximately 2 to 3 times under lower emissions and by 3 to 8 times under higher. Chicago can also expect a much longer heat wave "season," defined as the length of time between the first and last heat wave events of the year. Typically just under 70 days, this window is projected to widen by more than 1 to 2 months. This expanded interval of potentially hot days will require more sustained vigilance by the health-care sector to respond to heat stress ailments.

Using the definition of a "1995-like" heat wave, we therefore calculate the likely frequency of such an event occurring in future decades. Averaging results from the three different climate models used here, historical simulations suggest a 1-in-3 chance of having a 1995-like heat wave once during the 1980s and/or during the 1990s – when one, in fact, did occur. By mid-century, however, there are projected to be as many as 2 such heat waves each decade under the lower emissions scenario and almost 5 per decade, or one every other year, under the higher emissions scenario. By the end of the century, under lower emissions 1995-like heat waves can be expected on average every other year and approximately three times *each* year under higher emissions (Fig. 3).

Thus, although the people of Chicago are likely to become more acclimatized to higher temperatures over time (e.g., with increasing temperatures more people are likely to choose to install window and central air conditioning units), these results suggest that aggressive adaptation measures may be needed to prevent climate change-induced increases in extreme heat from taking their toll on Chicago's population.

Projected changes in offensive air mass days and heat-related mortality in Chicago

For the 30-year historical period 1961–1990, weather records indicate oppressive air masses over Chicago occurred on average about 16 days per year. Historical AOGCM simulations for the same time period produce oppressive air mass events on average 13 to 15 days per year, indicating that the models may slightly underestimate the frequency of such events (Fig. 4).

In the future, however, AOGCM simulations agree that the frequency of oppressive air mass events over Chicago is likely to

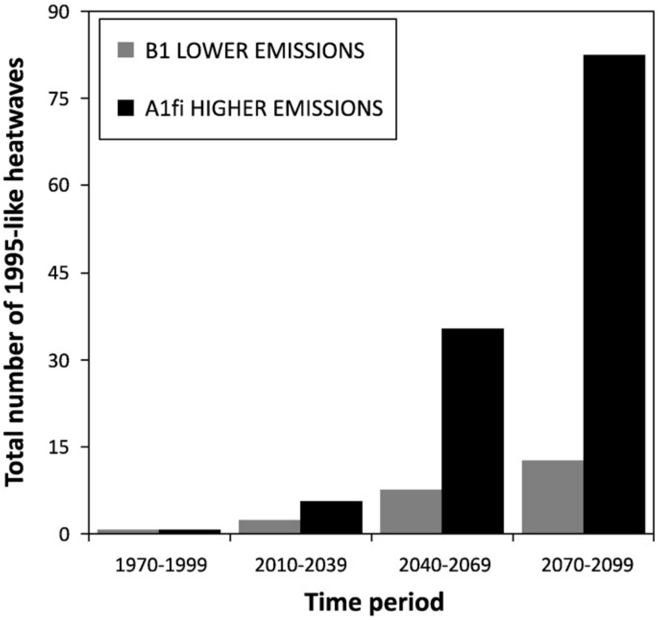

Fig. 3. Total number of 1995-like heat wave events observed (1970–1999) and projected to occur in each future time period, as simulated by GFDL CM2.1, HadCM3, and PCM under the SRES higher (A1fi) and lower (B1) emission scenarios.

increase. Over the next few decades, about 10 additional days per year are projected. By the middle of the century, there may be an average of almost 30 days per year under a lower emissions scenario and almost 50 days under the higher emissions scenario. By the end of the century, the average number of days per year that experience oppressive air mass events is projected to more than double under lower emissions, for a total of 34 days or more than a month. Under higher emissions, greater increases of more than four times historical values are projected, for an average of 72 days or almost two and a half months per year (Fig. 4).

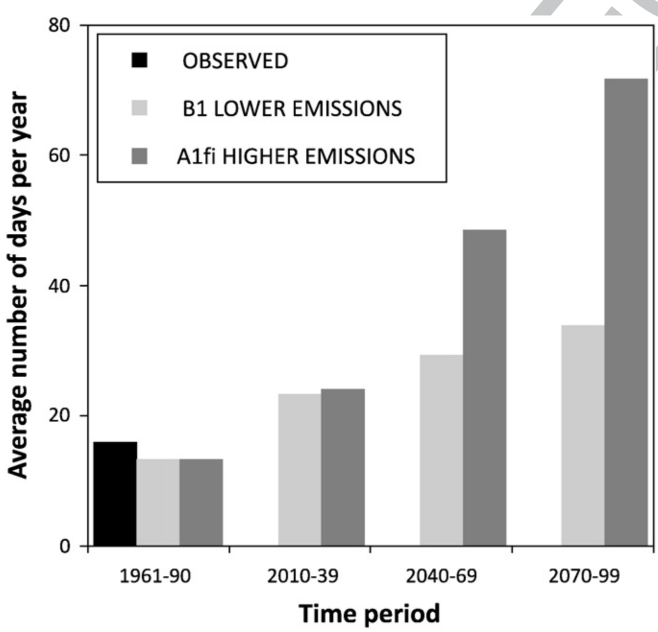

Fig. 4. Observed (black) and model-simulated (blue) average number of days per year where oppressive air masses (i.e., meteorological conditions that have been associated with elevated mortality rates in the past) occur over Chicago, as simulated by GFDL CM2.1, HadCM3, and PCM under the SRES higher (A1fi) and lower (B1) emission scenarios for the Chicago Midway weather station.

Table 1
Observed and model-simulated heat-related mortality rates. The average of GFDL CM2.1, HadCM3 and PCM projections is given, with the range shown in parenthesis based on the absolute values of the projections by the three AOGCMs. Units are average annual deaths per 100,000, based on a 1990 population estimate of 6.07 million for the Chicago metro area. These results do not take into account possible future adaptations such as changes in behavior, infrastructure, or public health strategies.

	Observed	Model-simulated	
		Lower emissions	Higher emissions
1961–1990	2.6	2.2 (2.0–2.3)	
2010–2039	–	4.7 (2.8–8.2)	
2040–2069	–	5.8 (4.2–8.4)	11.8 (4.9–20.6)
2070–2099	–	7.1 (4.0–10.8)	19.9 (7.8–32.6)

Although oppressive air mass events do not necessarily imply a heat wave (the event is required to last longer than a day or 2 to be classified as a heat wave), these results are consistent with previous research (Meehl and Tebaldi, 2004), which found that the circulation pattern associated with the 1995 heat wave is expected to become more frequent and be intensified by climate change, producing a greater number of “heat wave days” in the future.

Based on the model-simulated increases in oppressive air mass days, we then use the mortality Eqs. (1) and (2), derived from observed weather patterns and mortality rates, to estimate future mortality rates under higher and lower emissions scenarios. Projected future mortality rates for the population of Chicago are provided in Table 1, standardized to values per 100,000 by the average population for the Chicago metro area. The population of Chicago was assumed to be 6.07 million as given by the 1990 census, as this represents the closest population estimate to the mid-point of the historical mortality data. Comparing model-simulated with observed mortality rates for the historical period, once again it is evident that the model-based estimates are slightly lower than observed; this is likely a factor of the models underestimating the number of oppressive air mass events as noted previously. Note that mortality rates are not age-adjusted (i.e., we did not try to predict shifts in Chicago's demographic profile over time).

Over the coming decades, future projections indicate that average annual mortality rates are projected to increase significantly. For comparison, the mortality rate during the 1995 heat (using an estimate of 697 heat-related deaths in Cook County, with a metropolitan population of 6.07 million; Census, 2008) was 11.5 per 100,000. By the middle of the century under higher emissions, therefore, the average summer mortality rate for each year is expected to be similar to that during the actual heat wave in 1995. Before the end of the century, the average mortality rate is projected to be almost twice that, not accounting for any change in demographics over that time. Under the lower emissions scenario, increases of half that are expected, highlighting the important role of mitigation in minimizing the effects of extreme heat on urban mortality rates. It is important to note, however, that even over the next few decades, mortality rates are projected to double relative to their historic values regardless of emissions scenario. It is therefore essential to put in place adaptation strategies as well, as no mitigation strategy will be able to prevent changes over that time period that have already been built into the system by past emissions.

Another important feature of future changes in mortality rates is the projected increase in their year-to-year variability. The number of summer “extreme heat” events is projected to increase beyond what would be expected due to changes in the mean average temperature alone. This indicates a change in the standard deviation of the distribution of daily temperature, or the day-to-day variability. Thus, by the end of the century Chicago could experience summers very similar to those we experience today, side-by-side with summers where 1995-like heat wave conditions prevailed for weeks at a time. Similarly, estimates of projected year-to-year mortality rates over the

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Table 2
Standard deviation of model-simulated heat-related mortality rates per 100,000 under higher and lower emissions scenarios. In both cases, the standard deviation or year-to-year variability of mortality rates increases in the future, with larger increases under higher emissions as compared to lower and by end of century as compared to earlier time periods.

	Lower emissions	Higher emissions
1961–1990	2.6	
2010–2039	4.0	
2040–2069	4.7	6.3
2070–2099	5.3	6.4

coming century also indicate that seemingly "normal" summers could occur next to summers with mortality rates for the entire summer similar to or greater than those experienced during the 1995 heat wave.

One way of assessing this change in variability is through the standard deviation of the distribution of annual mortality rates, where the standard deviation is a measure of how far from the average value the actual value for an individual summer is likely to be.

Average year-to-year variability during the historical period is estimated to be 2.6 deaths per 100,000 – i.e., mortality rates during any given year was generally within the range of 2.6 ± 2.6 (Table 2). Within just a few decades the range is expected to increase to about 4, meaning that mortality rates are likely to be within the range of 4.65 ± 4. In other words, there could still be summers with little to no heat-related mortality, but there could also be summers where heat-related mortality averaged more than 8 deaths per 100,000 over the entire summer.

By the end of the century, the standard deviation is estimated to be 5.3 for the lower emissions scenario and 6.4 for the higher, meaning that for any given year, mortality rates per 100,000 could range from 0 to 16 under the lower emissions scenario and from about 2 (a normal value for the present day) up to 38 (almost double the mortality rates experienced during the 1995 heat wave) under the higher emissions scenario. This increase in variability has further implications for adaptation strategies, suggesting the need for a built-in flexibility to the public health system such that it is capable of absorbing large numbers of patients during the more extreme summers and next to none during more "normal" summers.

Estimating the effects of a 2003 EHW-like event on heat-related mortality in Chicago

An alternative way to assess the vulnerability of Chicago's population to a single extreme heat wave event is through an "analog city" analysis (Kalkstein et al., 2008). Here, the impact of a European 2003-like heat wave on the city of Chicago is estimated by transposing the meteorological conditions that occurred over Europe in the summer of 2003 to central North America instead. This analysis does not rely on any AOGCM projections for future changes in climate; rather, it simply assesses the potential impact of a single event on Chicago regardless of when it might be projected to occur, using the air mass approach described previously.

During a typical Paris summer, only 10% of summer days are classified as being within oppressive air masses (either Dry Tropical or Moist Tropical Plus). For both cities, more of the oppressive air mass days are categorized as DT rather than MT+. This is in contrast to other US cities, where MT+ air masses tend to be more common than DT (Kalkstein et al., 2008). For Chicago, these same types of oppressive air masses are typically present on 16 summer days or for about 17% of the summer (Fig. 4).

During the summer of 2003, however, almost half the days in Paris lay within an oppressive air mass. Similarly, for the Chicago analog summer modeled here, oppressive air masses are estimated to be present on 50 days or 54% of the summer – an exceptional event that has not occurred over the historical record. For both cities, more of the oppressive air mass days during the extreme EHW-like event are categorized as DT rather than MT+.

The number of consecutive days within oppressive air masses is also very unusual for the analog summer in both Paris and Chicago. Both cities experience three extended periods of consecutive oppressive air mass days over the course of the summer. For Chicago, the analog summer begins with a string of 14 MT+ days in June (with two transition days imbedded during that time), continues with a second string of 14 DT days in July (again with two transition days), and finishes with 15 consecutive DT days in August (Fig. 2b). The number of oppressive air mass days in each string is approximately equal to the entire summer average on a "normal" year.

Maximum and minimum temperature records during summer 2003 in Paris and for the analog summers for Chicago also exceed anything in recorded history (Fig. 2). In Paris, the all-time August maximum temperature record, set in 1911, was broken by almost 2 °C (3.6 °F) six times during the month, during two 3-day consecutive periods. From August 6 to 14, each day broke a daily maximum temperature record. For the Chicago analog, a similar number of maximum temperature records would be broken relative to the historical record (beginning in 1926).

Minimum temperatures were found to be equally oppressive during summer 2003 in Paris and the analog summer in Chicago. In Paris, the all-time summer high-minimum temperature record was broken by 1.5 °C (2.7 °F), and the all-time August record was broken by almost 3 °C (5.4 °F). Five days broke the all-time August high-minimum temperature record, comprising a three-consecutive day and a two-consecutive day string. Seven days in August broke the daily high-minimum temperature record during eight days between August 5th and 12th (Fig. 3).

In Chicago, an EHW analog event would break 12 daily maximum and minimum temperature records relative to the historical weather observations for Chicago dating back to 1926 (Fig. 3). Even more startling is the fact that 4 days would surpass the all-time maximum temperature record for Chicago and 8 days would exceed the all-time high-minimum temperature record. Many of these days would occur consecutively. This is important, as heat-related illnesses and deaths are generally more sensitive to minimum, rather than maximum, temperatures. Overnight heat provides little relief in non-air-conditioned dwellings.

Owing to these extreme and record-breaking heat conditions, historical heat-mortality relationships indicate that such a heat wave in Chicago would have an impact on public health exceeding that of the 1995 heat wave. Chicago's metro area now has slightly over 8 million people based on the year 2000 census, which would give Chicago a mortality rate for this heat wave of 13.4 deaths per 100,000 (in comparison, the 1995 heat wave, assuming a population of 6 million, had a mortality rate of 11.5 per 100,000). This indicates that Chicago's population is more sensitive to extreme heat than that of Detroit, Philadelphia, and Washington, but less sensitive than New York City and St. Louis (Kalkstein et al., 2008). To put this into further perspective, during an average summer in Chicago, about 94 people die from the heat. The analog city death total of 1073 is over 10 times that total. Clearly, a heat wave of this magnitude would tax the health care system even more than the heat wave of 1995.

Projected future occurrence and frequency of an EHW-like event

Finally, given the estimated significance of an EHW-like event for Chicago, how soon could such a heat wave be expected under future climate change? The importance of such a heat wave is in its actual impact on human health – which, as we have already seen, is a complex function of the duration, timing, and frequency of certain oppressive air mass types. For this reason, rather than calculate the air mass conditions that would lead to such an event, instead we simply cross-reference these mortality estimates with the year-to-year heat-

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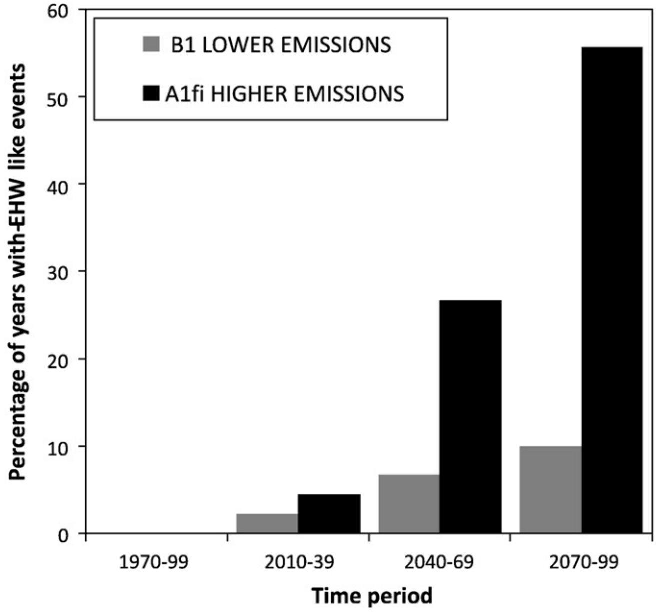

Fig. 5. Average number of summers per decade with mortality rates projected to equal those of the Chicago analog to the European Heat Wave of 2003, as simulated by GFDL CM2.1, HadCM3, and PCM under the SRES higher (A1fi) and lower (B1) emission scenarios for the Chicago Midway weather station.

related mortality estimates calculated in the heat-related mortality analysis previously, as this analysis was also based on the same air mass approach and mortality equations. In this way, we identify by when a similar number of deaths to what would be expected given a 2003 EHW-like event today might occur.

Our analysis suggests that an EHW-like event is very likely to occur over Chicago before the middle of the century, with all AOGCM simulations indicating at least one summer with mortality estimates over 1000 by 2050 (Fig. 5). The fact that an EHW-like summer is projected to occur within several decades under either the higher or the lower emissions scenario has important implications for adaptation, suggesting that even with stringent mitigation strategies, adaptive measures should be put in place to deal with such a situation.

EHW-like summers are likely to become even more frequent during the second half of the coming century. Under the lower emissions scenario, on average 5 more such summers are projected to occur before the end of the century, with the timing of the summers being primarily determined by random variability. Under the higher emissions scenario, however, 25 more EHW-like summers are projected to occur before the end of the century, with increasing frequency towards the end of the century. By 2070, for example, every second summer is projected to have mortality rates similar to or greater than those of the EHW analog summer (Fig. 5).

Discussion and conclusions

Significant increases in extreme heat, prolonged heat wave events, and heat-related mortality are projected to continue in coming decades, consistent with observed global trends in past decades (Alexander et al., 2006). Model uncertainties notwithstanding, extreme heat and associated human health risks under the higher emissions scenario are generally twice those projected to occur under lower emissions by end-of-century. These results suggest that more heat stress ailments can be expected in the future.

It is clear that extreme heat represents a growing threat to the City of Chicago – a threat shared by many other urban centers around the country. Precise mortality rates are uncertain given the importance of behavioral and infrastructure changes. However, increases in summer temperatures combined with more frequent, longer, and more intense extreme heat events to suggest that climate change could continue to pose a significant risk to human health over coming decades.

Several caveats must be kept in mind when interpreting these mortality estimates. First, as noted previously, they do not account for changing demographics. Many studies have shown that the elderly are more susceptible to extreme heat; others have indicated that there are racial differences as well, not all of which can be accounted for by socio-economic conditions (Whitman et al., 1997; Semenza et al., 1999; O'Neill et al., 2005; Browning et al., 2006). In addition, we have not accounted for the potential for adaptation measures such as increased air conditioning use. Although there is nearly complete market saturation of air conditioning in new residential housing, many older houses, apartments, and office buildings rely on window units only. Also, the present-day mortality rates in Chicago almost certainly reflect some contribution from the urban heat island effect (Changnon et al., 1996). Measures to reduce the urban heat island effect, as proposed by the Chicago Climate Action Plan,[1] could also aid in reducing mortality rates.

And lastly, the role of "harvesting" or displacement has not been accounted for in these figures. A proportion of the deaths that are attributable to heat are actually people who would have died shortly afterward from other causes (Kalkstein and Greene, 1997); for the 1995 Chicago heat wave, this value is estimated at 26% (Semenza et al., 1999), while for the 2003 EHW, it is estimated to range from zero to about 30% (Robine et al., 2008; Toulemon and Barbieri, 2008). Thus, future estimates include both the actual number of people who would have died of the heat, as well as those who would have died from other causes shortly after the heat event. As the number of oppressive air mass days grows to average many weeks each summer, however, essentially creating one long "heat wave" summer, this effect will become less and less important.

In summary, the second and third caveats would indicate that our numbers should be considered an upper bound for estimated heat-related mortality, as they do not factor in adaptation measures or displacement effects. The first caveat, however, suggests that these projections may underestimate future changes, since they do not factor in future demographic changes that are likely to increase the average vulnerability of the population.

It is important to note that demographic changes, societal decisions affecting adaptation, and changes in the health care sector will determine actual mortality rates. Significant efforts will have to be undertaken to provide effective early warning systems, public education, air conditioning, "cooling centers," and other adaptations (especially for the elderly, children, poor, and those already ill) to avoid major increases in the number of heat-related deaths. The urgency for such measures only grows in light of expected population increases and demographic shifts.

Heat watch-warning systems presently in operation in some major US cities have already been shown to save a number of lives when coupled with effective intervention plans (Ebi et al., 2004). Thus, such systems should prove to be an effective adaptive response tool if the climate warms as the projections suggest. The National Weather Service is now funding a project to develop more of these sophisticated systems that base warning thresholds upon human health outcomes. These systems, coupled with well-developed intervention activities, provide an adaptation mechanism to lessen the odds of very large increases in heat-related mortality in coming decades due to climate change.

Ultimately, however, the marked differences in projected heat wave frequency and associated mortality under a higher as compared to a lower emissions future emphasize the importance of mitigation policies. Near-term climate policies to reduce emissions have the potential to significantly reduce the risk of future health impacts.

[1] http://www.chicagoclimateaction.org.

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