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ORIGINAL ARTICLE

**Robert E. Davis · Paul C. Knappenberger ·
Wendy M. Novicoff · Patrick J. Michaels**

Decadal changes in summer mortality in U.S. cities

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Abstract Recent studies suggest that anthropogenic climate warming will result in higher heat-related mortality rates in U.S. cities than have been observed in the past. However, most of these analyses assume that weather-mortality relationships have not changed over time. We examine decadal-scale changes in relationships between human mortality and hot, humid weather for 28 U.S. cities with populations greater than one million. Twenty-nine years of daily total mortality rates, age-standardized to account for underlying demographic changes, are related to afternoon apparent temperatures (T_a) and organized by decade for each city. Threshold T_a values, or the T_a at and above which mortality is significantly elevated, are calculated for each city, and the mortality rates on days when the threshold T_a was exceeded are compared across decades. On days with high T_a, mortality rates were lower in the 1980s and 1990s than in the 1960s and 1970s in a majority of the cities. Regionally, northeastern and northern interior cities continue to exhibit elevated, albeit reduced, death rates on warm, humid days in the 1980s and 1990s, while most southern cities do not. The overall decadal decline in mortality in most cities is probably because of adaptations: increased use of air conditioning, improved health care, and heightened public awareness of the biophysical impacts of heat exposure. This finding of a more muted mortality response of the U.S. populace to high T_a values over time raises doubts about the validity of projections of future U.S. mortality increases linked to potential greenhouse warming.

Keywords Human mortality · Climate change · Heat stress · Apparent temperature · United States

R. E. Davis (✉) · P. J. Michaels
Department of Environmental Sciences, University of Virginia,
P.O. Box 400123, Charlottesville, Virginia, 22904-4123, USA
e-mail: red3u@virginia.edu
Tel.: +1-434-924-0579
Fax: +1-434-982-2137

P. C. Knappenberger
New Hope Environmental Services, 5 Boar's Head Lane,
Charlottesville, Virginia, 22903, USA

W. M. Novicoff
Department of Health Evaluation Sciences, School of Medicine,
Box 800717, Health Sciences Center, University of Virginia,
Charlottesville, VA 22908, USA

Introduction

One of the most important potential impacts of human-induced climate change would be higher rates of heat-related human mortality. Increases in the heat index have been observed in the United States (Gaffen and Ross 1998) and warming induced from urban heat islands has raised the average temperature experienced by most of the U.S. populace (e.g., Landsberg 1981). Some forecasts suggest that heat-related death rates in U.S. cities could double by 2020 and increase severalfold by 2050 [Kalkstein and Greene 1997; Chestnut et al. 1998; National Assessment Synthesis Team (NAST) 2000].

Human mortality rates tend to be significantly higher on hot and humid days, particularly in northern U.S. cities (Oeschli and Buechli 1970; Bridger et al. 1976; Kalkstein and Davis 1989; Kalkstein and Greene 1997; Davis et al. 2002). In a large majority of cases, however, the primary cause of death is one of a broad class of circulatory or respiratory diseases that are not typically considered to be "heat-related" (Keatinge et al. 1986; Larsen 1990a, b; Kilbourne 1997). Therefore, heat is considered a mortality correlate rather than a direct cause of death in most instances.

Future mortality rate projections are typically derived from the extrapolation of historical weather-mortality relationships linked to hypothesized or modeled future climate conditions (Kalkstein and Greene 1997; Chestnut et al. 1998; Gaffen and Ross 1998; NAST 2000). This approach implicitly assumes that the response of mortality to weather has been and will remain constant over time. In other words, the joint mortality-weather times series is assumed to be stationary (for example, an incremental increase in the heat index will produce roughly the same incremental increase in age-adjusted mortality, in a given city, in both 1970 and in 1990). If, however, historical weather-mortality relationships have changed (i.e., if the mortality response differs significantly for the same climate conditions over time), then this temporal variability could bias future mortality predictions.

The goal of this research is to determine if decadal-scale changes are evident in weather-mortality relationships in major U.S. metropolitan areas from 1964–1998. Thus, our null hypothesis is that weather-mortality relationships have not changed over time in U.S. cities.

Data and methods

Mortality data

Daily mortality data are culled from National Center for Health Statistics data archives, which include the date, county, and cause of death for each person who died in the United States from 1964 to 1998 as well as their age, race, and sex (National Center for Health Statistics 1998). Because the date of death was not recorded in this digital archive between 1967 and 1972, our records include 29 non-consecutive years of data. Our analysis ends in 1998 because subsequent years had not been digitally archived at the time this research was completed.

Daily deaths are totaled for 28 metropolitan statistical areas (MSA) with a 1990 population of at least one million residents. Our database includes most of the largest MSA for which representative surface weather observations were readily available. Mortality analyses undertaken at the daily level require the use of large cities to produce relatively stable and statistically robust mortality time series. The counties that comprise each MSA are in accordance with the 1990 U.S. Government definitions.

Raw mortality totals cannot be directly compared over time or between cities because of inherent demographic differences. For example, a city with an aging population should have higher death rates than another city with a younger populace or the same city several decades earlier. To facilitate both inter- and intra-city comparisons, daily mortality counts are age-adjusted to that of a "standard city" with a population of one million people on the basis of the age distribution of the population of the United States in the year 2000 (Anderson and Rosenberg 1998). This direct standardization method, a common epidemiological technique, is performed using U.S. Census information from 1960, 1970, 1980, 1990, and 2000 for ten age categories and the population of intervening years is linearly interpolated (United States Department of Commerce 1973, 1982, 1992, 2001). Age-standardized daily mortality serves as the basis of all subsequent analyses.

The total daily mortality (all causes) is used as our dependent variable instead of a stratified subsample. Prior research has demonstrated that the strongest weather-mortality relationships are typically found for the total daily mortality rather than subsets of specific causes of death related to heat (Applegate et al. 1981; Jones et al. 1982; Kalkstein and Davis 1989; Kunst et al. 1993). Heat exposure is only rarely identified on a death certificate as the primary cause of death but heat can be a confounding factor in cerebrovascular and cardiopulmonary mortality (Kilbourne 1997), both of which are among the leading causes of death in the United States. [The current lack of consistently applied criteria for classifying a particular death as "heat-related" has led to the call for more universal standards (Semenza et al. 1996)].

For decadal-scale comparisons, the mortality records are organized into three "decades:" 1960–1970s (1964–1966 and 1973–1979; 10 total years); 1980s (1980–1989; 10 years); and 1990s (1990–1998; 9 years). The 1960s and 1970s are combined into one "decade" because of the lack of useable daily data in the late 1960s and early 1970s.

Fig. 1 Metropolitan Statistical Areas (MSA) used in this study. See Table 1 for station identifiers

Study cities

The stations examined in this study are shown in Fig. 1. Since large daily samples (high daily death rates) are needed to assure statistical robustness, only MSA with populations in excess of one million residents in 1990 are included. No effort was made to insure a representative spatial sample, so the resulting distribution reflects the higher population density in the northeastern United States and along the coastal regions.

Weather data

Weather data are sampled from an appropriate first-order National Weather Service recording station for each MSA (Table 1) (National Climate Data Center 1993; National Environmental Satellite, Data and Information Service 2000). In some climatological research, it is necessary to select stations that are relatively free of possible contamination from the urban heat island. In this case, however, since most residents live and work within the urban–suburban ring, any heat-island "biases" are probably more reflective of the temperatures commonly experienced by residents. We assume that observations from a single weather station are roughly representative of conditions across the MSA. This is generally true in a convectively well-mixed boundary layer in summer, our primary season of interest. Nevertheless, the precise location of the weather station can be important and may not be representative in some cities, particularly in topographically variable regions such as mountains and coastlines. These siting issues should be considered when results between MSA are compared.

We use the apparent temperature (T_a) at 4 p.m. Local Standard Time (LST) as our independent variable. T_a, a measure of the "sultriness" of the air (Steadman 1979), combines air temperature and humidity in a single variable. Although numerous other heat stress measures exist (e.g., Kilbourne 1997; Höppe 1999; Matzarakis et al. 1999; Laschewski and Jendritzky 2002), T_a is the basis of the heat index used by the U.S. National Weather Service in issuing heat advisories. Our use of T_a in this research does not necessarily imply that it is the ideal variable for weather-mortality studies. However, T_a is easily calculated from readily available weather observations, which at least partially accounts for the pervasiveness of this index. From the mid-1960s to the late-1970s, many first-order weather-station readings were taken at 3-h rather than 1-h intervals. Because observations were not gathered at 4 p.m. in the Central and Mountain Time Zones, the 4 p.m. LST temperature and dew point temperature were linearly interpolated at these stations.

Because mortality records consistently exhibit a time lag between the weather stressor and the mortality response, the most oppressive days typically do not have the highest mortality rates. After testing several possible lag relationships, a 1-day lag was

Table 1 Meteorological stations associated with each metropolitan statistical area. *WBAN* Weather Bureau Army and Navy

Abbreviation	WBAN number	Meteorological station
ATL	13874	Atlanta Hartsfield International Airport
BAL	93721	Baltimore-Washington International Airport
BOS	14739	Boston Logan International Airport
BUF	14733	Buffalo Niagara International Airport
CHI	94846	Chicago O'Hare International Airport
CHL	13881	Charlotte Douglas International Airport
CIN	93814	Cincinnati Northern Kentucky Airport
CLE	14820	Cleveland Hopkins International Airport
DAL	03927	Dallas-Fort Worth International Airport
DEN	23062	Denver Stapleton International Airport/ Denver International Airport
DET	94847	Detroit Metropolitan Airport
HOU	12960	Houston Bush Intercontinental Airport
KSC	03947	Kansas City International Airport
LAX	23174	Los Angeles International Airport
MIA	12839	Miami International Airport
MIN	14922	Minneapolis-St. Paul International Airport
NOR	12916	New Orleans International Airport
NYC	14732	New York Laguardia Airport
NFK	13737	Norfolk International Airport
PHI	13739	Philadelphia International Airport
PHX	23183	Phoenix Sky Harbor International Airport
PIT	94823	Pittsburgh International Airport
POR	24229	Portland International Airport
SEA	24233	Seattle-Tacoma International Airport
SFC	23234	San Francisco International Airport
STL	13994	St. Louis Lambert International Airport
TAM	12842	Tampa International Airport
WDC	13743	Washington Reagan National Airport

incorporated throughout the analysis such that the death rate on day 2 is related to the 4 p.m T_a on day 1. This finding of a 1-day lag in summer is supported by previous studies (Rogot and Padgett 1976; Bull and Morton 1978; Kalkstein and Davis 1989; Gorjanc et al. 1999).

Mortality seasonality

In most cities in the United States, Canada, and parts of Eurasia, there is an inherent seasonality in mortality with higher death rates in the cold season (Langford and Bentham 1995; Donaldson and Keatinge 1997; Eurowinter Group 1997; Lerchl 1998). For example, a scatter plot of daily mortality in New York City against 4 p.m. T_a shows increasing mortality at both high and low T_a values (note that T_a equals air temperature below 20 °C) (Fig. 2a). Although reasons for this seasonality are uncertain, the seasonal differences are relatively more pronounced in certain disease categories (Donaldson and Keatinge 1997; Eng and Mercer 1998; Danet et al. 1999; Kloner et al. 1999; Pell and Cobbe 1999; Donaldson et al. 1998; Lanska and Hoffmann 1999; McGregor 2001). This inherent seasonality could potentially bias any daily weather-mortality analysis. For example, a relatively warm day in March might have a higher mortality rate than a day with similar weather in July simply because March mortality is higher on average. To remove the seasonal component of mortality, each day's mortality total is "de-seasoned" by subtracting from it the median mortality of that month. In the de-seasoned scatter plot for New York City (Fig. 2b), there is still strong evidence of a daily T_a-mortality relationship on hot and humid days but the winter peak is no longer evident.

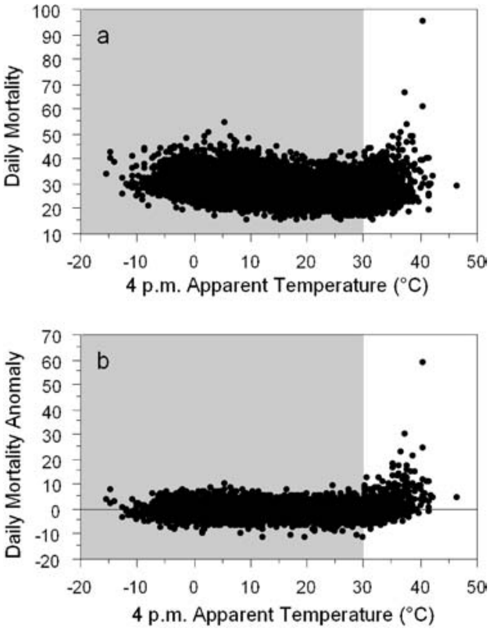

Fig. 2 **a** Population-adjusted daily mortality versus 4:00 p.m. Local Standard Time (LST) apparent temperature (°C) for the New York City MSA. **b** De-seasoned population-adjusted daily mortality versus 4:00 p.m. LST apparent temperature (°C) for the New York City MSA. Apparent temperatures above the threshold apparent temperature (30 °C) are plotted in the white regions

Threshold apparent temperature

Over most of the range of T_a and in most cities, there is little relationship between mortality and T_a. But for some cities, de-seasoned mortality tends to increase as the highest T_a values are approached. New York City (Fig. 2b) has higher death rates on days when 4 p.m. T_a values exceed about 30 °C. The lack of a mortality-T_a relationship over most of the T_a range and the increased mortality on hot and humid days argue for the existence of a threshold apparent temperature, or the T_a at and above which mean mortality rates are significantly elevated above the baseline. To calculate the threshold T_a for each city, de-seasoned daily mortality counts are computed for a 2 °C T_a moving window incremented by 1 °C T_a. For each 2 °C-wide class interval, a one-sample, one-tailed *t*-test is performed to determine if the mean mortality is significantly greater than zero ($\alpha \leq 0.05$). Then, for increasing T_a, the first class interval for which the null hypothesis that the mortality rate is not different from zero is rejected is identified as a threshold T_a candidate. If all higher T_a categories have mean mortality rates greater than zero, then an additional *t*-test is performed to determine if the mean mortality rate of all observations equal to and above the threshold T_a candidate temperature is significantly above zero. The goal of this procedure is to identify the T_a that marks the lowest value at which mortality rates become significantly elevated above the long-term baseline. The actual threshold T_a is chosen as the mean T_a of the lowest T_a class interval that significantly exceeds the mean. Because class interval sample sizes become small for high T_a, we only consider class intervals with sample sizes of at least 5 days. This criterion adds statistical robustness to our threshold T_a estimates. (Throughout the remainder of this paper, days in which T_a *equals* the threshold T_a will be considered *above* the threshold to improve readability. For example, the New York threshold T_a is 30 °C, so days on which the 4 p.m. LST T_a equaled 30 °C will be considered days that "exceeded" the threshold T_a).

In New York City, for example, mortality is significantly above zero for the class interval 29.0 °C–30.9 °C, on the basis of a one-tailed *t*-test (Fig. 3). Mean mortality remains above normal for all class intervals with higher T_a, excluding those with class sample sizes of five or less. Based on the candidate threshold T_a of 30 °C, a final *t*-test is performed to determine if the mean mortality is significantly elevated for all days with 4 p.m. T_a values greater than or equal to 30 °C. Since this test is passed at the 0.05 level (the null hypothesis of no difference is rejected), the New York threshold T_a is calculated to be 30 °C.

Threshold T_a values are determined using the composite data for the "decade" of the 1960–1970s only. As our null hypothesis is that weather-mortality relationships are time-invariant, this requires us to use the earliest period to determine the threshold T_a which is then held constant in subsequent decades. Given either increasing or, at a minimum, constant T_a over time in the United States (Gaffen and Ross 1998), this is the most conservative method for examining changing mortality responses to an underlying climate that might also be changing. While it would also be interesting to examine if threshold T_a values have changed over time, this aspect is beyond the scope of our current research but is the topic of an ongoing, parallel study.

Hypothesis testing: changes in decadal weather-mortality relationships

Our fundamental goal is to determine if daily weather-mortality relationships have changed across decades. For each "decade" (1960–1970s, 1980s, and 1990s) the mean de-seasoned mortality anomaly for all days above the threshold T_a is compared to all other decades and to zero. In the former comparisons, a two-sample, two-tailed *t*-test is performed to determine if differences exist between decadal pairs. The Tukey/Kramer test is used to account for the multiple comparison problem of biasing the type I error rate (original $\alpha \leq 0.05$) (Milliken and Johnson 1984). In the latter case, a one-sample, one-tailed *t*-test is applied to determine if each decade's heat-related mortality rate is significantly greater than zero ($\alpha \leq 0.05$).

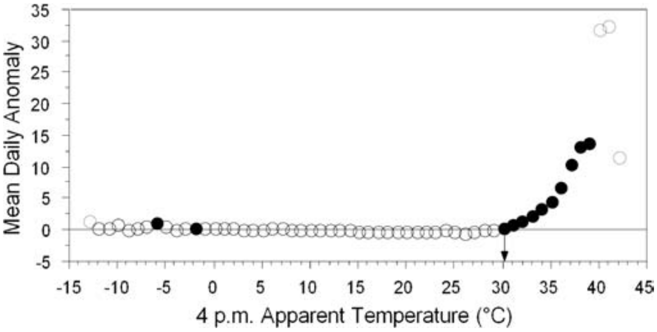

Fig. 3 Average de-seasoned population-adjusted daily mortality for 2 °C apparent temperature class intervals plotted at the interval midpoint for the New York City MSA. *Filled circles* Class intervals with significantly elevated mortality, on the basis of a one-sample, one-tailed *t*-test (α=0.05). *Open circles* Class interval means without significantly elevated mortality. *Gray circles* Class intervals with five or fewer observations. *Arrow* Threshold apparent temperature: 30 °C

Summary of methods

Daily mortality data are first age-standardized relative to a base population to allow for intercity and interdecade comparisons and then lagged by 1 day. Because mortality has an inherent seasonal cycle that could bias interpretation of the impacts of specific weather events, the mortality data are de-seasoned by subtracting each month's median number of deaths. Each city is then examined for the existence of a threshold T_a, or the T_a above which mortality rates are significantly elevated, by computing the mean mortality in 2 °C-wide T_a class intervals that overlap by 1 °C. The threshold T_a is calculated as the lowest T_a class interval with significantly elevated mortality rates for which all higher T_a class intervals exhibit above normal mortality. Mortality data are grouped into three "decades," and decadal mortality rates for days above the threshold T_a are compared to each other and to zero using *t*-tests.

Results

Over much of the range of T_a values and in most cities, there is little relationship between mortality and T_a. But for some cities, particularly those in the northeastern quadrant of the United States, mortality tends to increase as the T_a extremes are approached (Bull 1973; Rogot and Padgett 1976; Bull and Morton 1978; Wyndham and Fellingham 1978; Alderson 1985; Kalkstein and Davis 1989; McKee 1990; Curwen 1991; Kunst et al. 1993; Khaw 1995). For example, New York City (Fig. 2a) has higher death rates at the extremes of the T_a distribution and higher mortality in winter than in summer. The impact of the seasonal mortality cycle is evident when it is directly compared with the de-seasoned scatter plot (Fig. 2b). The relationship between high T_a and daily mortality remains or is strengthened but the winter relationships are lost. This result is common in most "weather-sensitive" cities.

To examine decadal mortality changes, the New York City daily mortality anomalies from Fig. 2b are subdivided by decade (Fig. 4). (Recall that the number of available years in each decade varies slightly.) For days

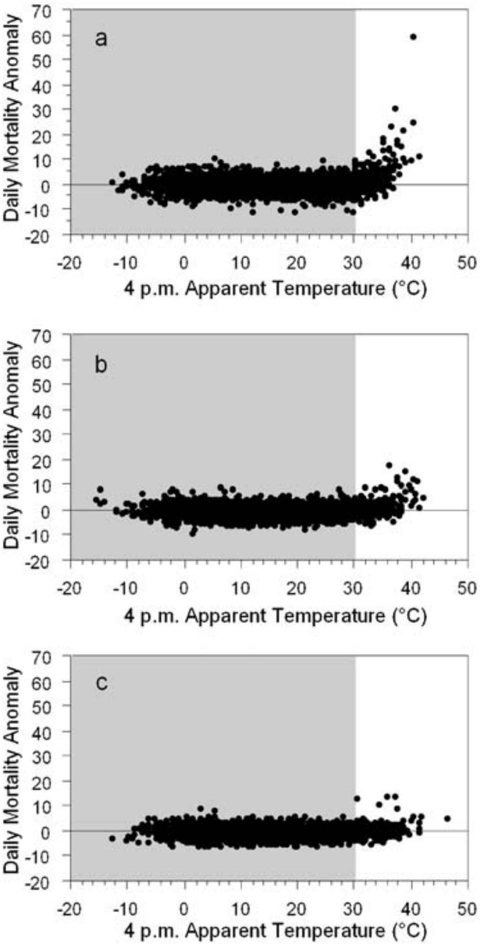

Fig. 4a–c New York City MSA de-seasoned and population adjusted daily mortality versus 4 p.m. LST apparent temperature (°C) organized by "decades" (**a**) 1964–1966 and 1973–1979, (**b**) 1980–1989, (**c**) 1990–1998. Apparent temperatures above the threshold apparent temperature (30 °C) are plotted in the white regions

that exceed the threshold T_a, visual inspection shows an obvious decline in the anomaly mortality over time. Although mortality still appears to be elevated above the threshold T_a in the 1990s, this elevation is minimal in comparison to the 1980s and is much smaller than in the 1960s–1970s.

Threshold apparent temperature regionality

There is a fairly strong regional consistency in human mortality responses to high T_a (Fig. 5). In the northeastern quadrant, threshold T_a vary from about 28 °C to 32 °C. In the typically warm and humid southeastern quadrant, threshold T_a are much higher (37–38 °C). There is also evidence of a transition region where threshold T_a fall between those of the northeast and the south, although the values are less spatially coherent. Norfolk has a threshold T_a a few degrees higher than the proximate locations of Washington D.C. and Charlotte, and Kansas City has a higher threshold than St. Louis. Thresholds along the West Coast and in Denver do not exhibit the same regional consistency as the northeastern and southern cities and include the lowest threshold T_a of any MSA (24 °C in Los Angeles and 26 °C in San Francisco). So in general, although there are small variations within regions, the MSA with warmer, more humid summers tend to have the highest threshold T_a while characteristically cooler locales have much lower thresholds.

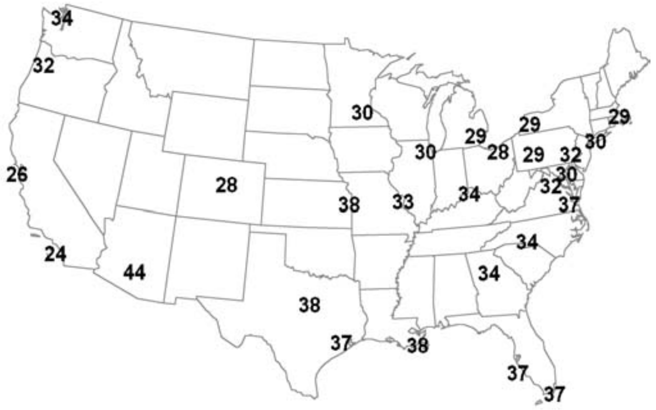

Fig. 5 Threshold 4 p.m. LST apparent temperature (°C) for each of the 28 MSA

Decadal comparisons

Our underlying null hypothesis is that weather-mortality relationships have not changed over decades. To examine this, for each MSA, decadal mortality anomalies (on days when the threshold T_a was exceeded) are compared to each other and relative to the mean (zero, since de-seasonalization yields mortality anomalies) (Fig. 6).

A threshold T_a was present in all of the 28 study cities in the earliest "decade," indicating that all MSA exhibited significantly elevated mortality at the high end of the T_a range. By the 1980s, for T_a above the 1960s–1970s threshold, 6 cities no longer show evidence of elevated mortality and 10 others demonstrate a statistically significant decline in average daily mortality compared to the 1960s–1970s. All of the cities with significantly lower mortality rates in the 1980s are in the Northeast. By the 1990s, 10 of the 28 MSA show no significantly elevated mortality on days when weather conditions exceed the threshold T_a. At these locations, there is no demonstrable impact of high temperatures and humidity on human mortality rates. Of the remaining 18 cities that are still weather-sensitive in the 1990s, 12 exhibit statistically significant declines in mortality rate in either the 1980s, the 1990s, or both, relative to the rates in the 1960s–1970s. In these cities, the populace is less influenced by high T_a now than it was previously, even though there continues to be evidence of elevated mortality on hot, humid days. In only 6 of the 28 cities – Atlanta, Buffalo, Dallas, Denver, Seattle, and San Francisco – is mortality

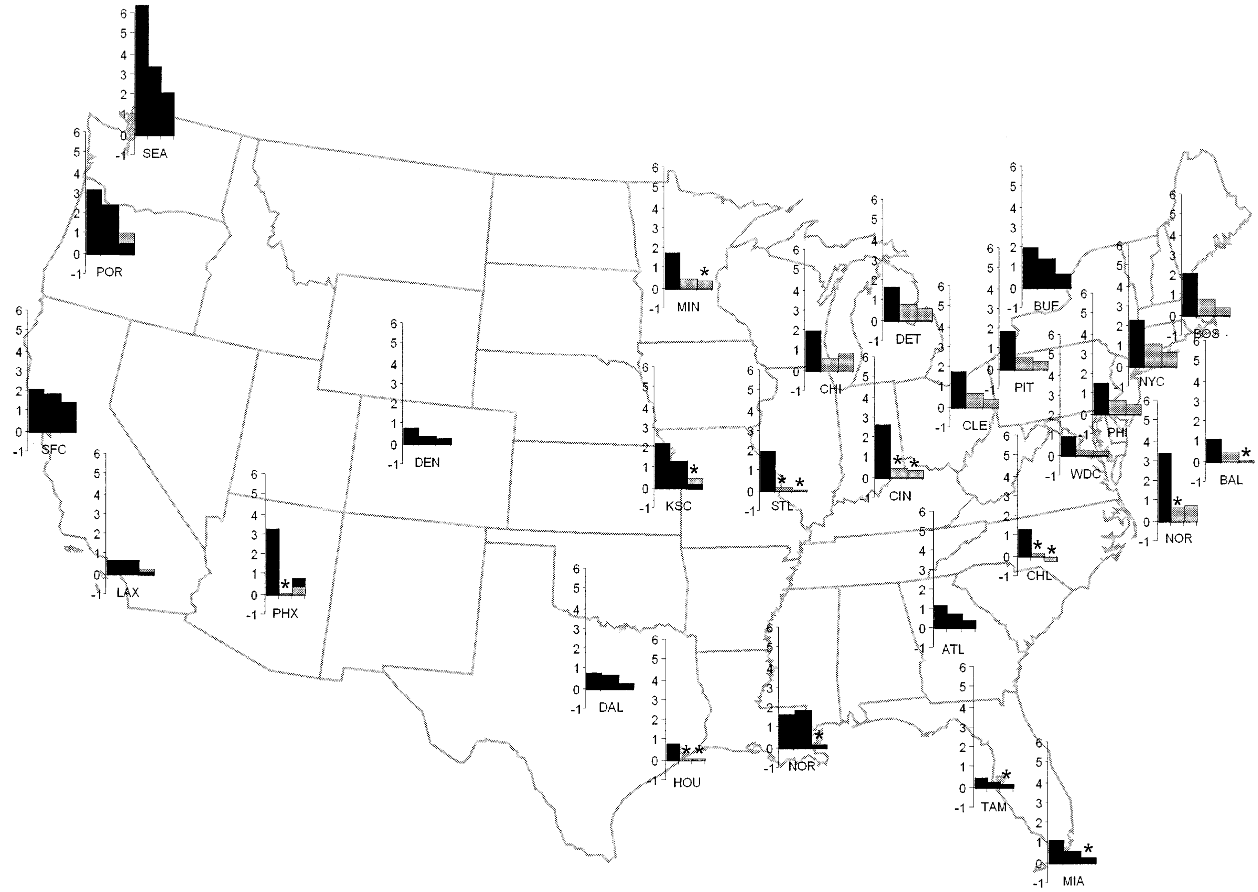

Fig. 6 The average daily mortality anomaly above the threshold apparent temperature during each "decade" for all 28 MSAs. The bars are ordered by "decade" (1964–1966 and 1973–1979, 1980–1989, 1990–1998 successively) for each city. Decades indicated by *gray bars* are statistically different from the decades plotted with *black bars*, and *asterisks* (*) above bars indicate that the average mortality anomaly for that decade is not statistically different from zero. In the decade of the 1990s, some bars have two colors. In these cases (*LAX, PHX, POR*) the color of the top half of the bar represents the association between the 1990s and the 1960s/1970s and the color in the lower half of the bar represents the comparison between the 1990s and the 1980s

both elevated and significantly unchanged over the past three decades. In all 6 cases, the death rates have declined for each decade, but the relationships are not sufficiently statistically robust to demonstrate that the decreases are real. Overall, the body of evidence indicates that we can reject our null hypothesis that weather-mortality relationships have not changed over time.

There is fairly strong regional consistency to the decadal mortality changes. Cities in the northeastern quadrant show evidence of excess deaths on hot, humid days in the 1990s. This includes all cities from Washington D.C. northward and westward to Chicago. But in most cases, mortality rates are lower in the 1990s than in the 1960–1970s, often significantly so. Outliers include Baltimore, where 1990s mortality is not elevated, and Buffalo, where there is no demonstrable decadal decline. In most southern cities, hot and humid weather had no significant influence on death rates in the 1990s. In other words, on the basis of our threshold definition, the populations in these southern cities are no longer sensitive to high heat and humidity. The exceptions to this prevailing pattern are Atlanta and Dallas, where mortality rates are generally low but nevertheless remain above average in the 1990s. Cities in the western United States have varied responses that are not regionally consistent. Denver, where threshold T_a are most often exceeded, has the lowest relative mortality rate of any city even though there is evidence of a relationship with T_a. Conversely, San Francisco and Seattle have high relative mortality rates, elevated mortality on hot days, and show no evidence of significant mortality declines over time. Portland, Los Angeles, and Phoenix exhibit some mortality rate declines over time in some decadal comparisons.

For days in which the threshold T_a was surpassed, the relative daily death rate (which can be considered "excess deaths") was summed for each year at each MSA and then averaged by "decade" (Fig. 7). This calculation incorporates both changes in the background climate and the evolving interplay between weather conditions and mortality rates. Despite generally increasing T_a (Gaffen and Ross 1998) and thus more days above the threshold T_a, excess deaths have systematically declined in the 1990s in almost every city. Averaged nationally, the rate of excess deaths on hot, humid days dropped from about 53 per

Fig. 7 Annual average excess deaths (for days that exceed the threshold apparent temperature) for each MSA, by decade. For each MSA, the first bar represents the "decade" of the 1960s–1970s, the middle bar the 1980s, and the third bar the 1990s. The average of all 28 MSAs is shown in the *lower left*. Deaths have been age-standardized relative to a normal population to allow for direct comparisons over time and between cities

million population per year in the 1960s–1970s to 25 in the 1980s and 15 in the 1990s. Summer weather sensitivity is still evident in the 1990s in the northeastern U.S. where annual death rates generally exceed those of southern cities across all decades.

Discussion

The relationship between daily mortality and afternoon T_a has changed over time, particularly in cities in the northeastern quadrant of the United States where excessive heat and humidity are relatively uncommon. In the 1960s and 1970s, northeastern cities exhibited higher mortality rates than southern cities on hot and humid days. These regional differences argue for an adaptation response at the MSA scale. By the 1990s, many of the previously weather-sensitive northeastern cities experienced statistically significant mortality declines for the same T_a. There are many possible reasons for these decadal-scale changes:

1. Increased use of air conditioning in homes, cars, and offices
2. Advances in medical care
3. Increasingly proactive measures taken by local agencies in response to forecasts of potentially dangerous weather conditions
4. Human biophysical adaptations
5. Infrastructural and architectural adaptations to summer heat.

It is difficult to quantify the extent to which air conditioning mitigates mortality, but estimates vary from 21% to 98% (Rogot et al. 1992; Kalkstein 1993; Semenza et al. 1996; Kilbourne 1997; Chan et al. 2001). Air-conditioned homes are becoming more commonplace in regions that previously did not include this amenity, particularly in the northeastern U.S. where mortality rates have declined most significantly. Some localities have begun instituting systems of warning residents on days when conditions that typically lead to high mortality have been forecasted (Kalkstein et al. 1996; McGeehin and Mirabelli 2001; Palecki et al. 2001). Human biophysical acclimatization has been shown to take place both within a given season and over longer periods of time (Marmor 1975; Bonner et al. 1976; Wyndham et al. 1976; Greenberg et al. 1983; Frost and Auliciems 1993; Kalkstein 1993).

The overall regional differences in weather-mortality relationships support the hypothesis that, because of biophysical and behavioral adaptations, mortality increases with respect to relative rather than absolute environmental conditions. For example, although mortality tends to rise when the 4 p.m. T_a exceeds about 30 °C in New York, there is no comparable response in Houston where the threshold T_a is 7 °C higher. Apparently, the populace of the Houston metropolitan area is accustomed to these hot and humid conditions.

But what role have adaptations played over time? Let us assume that T_a has increased over time. If the threshold T_a remains fixed and mortality rates (above the threshold) increase, this would indicate that little or no adaptation has occurred. Alternatively, if the threshold T_a increases and mortality rates remain constant, this would suggest that an approximately fixed proportion of the population in a given city is weather-sensitive and susceptible to the *relative* heat and moisture conditions. In this latter case, some degree of adaptation has occurred. Although we use a fixed threshold T_a, our results argue for a rather significant adaptation response throughout the metropolitan populace. Mortality rates are declining in most cities (Fig. 7) despite steady or increasing T_a across the United States (Gaffen and Ross 1998). It would nevertheless be interesting to examine if threshold T_a have changed over time. Recall that our null hypothesis of stationarity requires that we fix the threshold T_a, which we based on the 10 years available in the 1960s and 1970s. We are currently studying how mortality rates have changed while allowing the threshold T_a to vary across decades.

The spatial pattern of both threshold T_a and decadal mortality changes is fairly consistent, particularly in the eastern two-thirds of the United States (and about 75% of the cities). Despite large racial, ethnic, socioeconomic and infrastructural differences between these cities, this regional consistency supports our premise that weather and climate conditions influence mortality rates. If we had observed large differences in the weather-mortality response between nearby MSA, this would have provided evidence that mortality responses are dominated by local rather than larger-scale factors. Although there are certainly many important, local factors that affect daily mortality rates within each MSA, we believe the spatial consistency of our results indicates that climate has an important influence on regional differences in heat mortality across the United States.

In contrast to the other stations, the six MSA west of the Rockies are not regionally consistent. In Los Angeles, the threshold T_a of 24 °C is surprisingly low. Our weather station for Los Angeles is the Los Angeles Airport, located on the coast. Observations at the airport are not representative of the diverse weather experienced across the greater Los Angeles MSA. Similar difficulties are present at San Francisco, where we are also using coastal airport data. However, the 26 °C threshold T_a is rarely exceeded at San Francisco or Portland, Oregon (only about 12 days per year at each site). The Seattle threshold T_a of 34 °C is very high for a station with a maritime climate and is reached only about once per year. These relatively high threshold T_a in Seattle and Phoenix account for the low annual excess death totals at these locales (Fig. 7). Whether or not the weather station is representative might also be an issue in the Denver MSA. Other potential confounding factors include substantial shifts in the racial demographics related to significant emigration within MSA (our standardization procedure accounts for changing age demographics but not changes in racial composition). This, coupled with changing socioeconomic status in some MSA, could impact mortality-weather relationships. It is noteworthy, however, that no physiological disposition to heat vulnerability based on race has been identified (Kilbourne 1997). Furthermore, the potential confounding influence of weather and air quality is a major issue in the western United States where static stability is higher, particularly in the warm season. The relative impact of human exposure to airborne pollutants and weather remains unresolved (e.g., Kalkstein 1993; Katsouyanni et al. 1993; Samet et al. 1998; Bernard et al. 2001). It is clear that additional research is needed to sort out weather-mortality relationships in these western MSA.

This research has focused on the collective of high – T_a days within each city; we did not account for heat waves per se. In a related study, we are investigating mortality responses to comparable heat waves over time. This is somewhat more complicated, however, since more people tend to die earlier in a given heat wave or in early-season as opposed to late-season heat waves. This "mortality displacement" effect suggests that more susceptible individuals might succumb to the onset of a stress-inducing weather event, leaving behind a healthier population (Gover 1938; Schuman et al. 1964; Schuman 1972; Marmor 1975; Lyster 1976; Kalkstein 1993; Kilbourne 1997; Smoyer et al. 2000). Within-season adaptation responses may also play a role in this observation (Marmor 1975; Greenberg et al. 1983; Kalkstein 1993; WHO/WMO/UNEP 1996).

Our results are somewhat sensitive to the method used to determine the threshold T_a. Previous papers by the lead author (Kalkstein and Davis 1989) and this research group (Davis et al. 2002) have used different methods of calculating the threshold T_a. Careful inspection of scatter plots of mortality versus T_a supports the existence of a heat and humidity condition above which mortality tends to increase that varies between cities. However, small sample sizes with high T_a values (since the more extreme conditions are rare) coupled with the need to examine temporal changes (in this case, at the decade scale) makes the identification of the "real" threshold T_a problematic and somewhat arbitrary. In this paper, we propose that a threshold T_a exists only when there is a statistically significant increase in mortality for the composite of all days at or above that value. If the class interval for a higher T_a has a mean mortality rate below zero (the long-term normal), then it is difficult to argue for the existence of a threshold T_a that is lower. We would anticipate that the calculation of a threshold T_a would become easier as sample sizes increase, but given our demonstrated temporal changes in weather-mortality relationships, this matter might remain a point of contention for some time. Despite these concerns, the general pattern of results is similar to that found in our other work (Davis et al. 2002): northern MSA have higher weather sensitivity and southern MSA have higher threshold T_a and little elevated mortality when the threshold is exceeded.

Despite recent progress, many issues in weather-mortality relationships remain unresolved. Reasons for the significant differences in winter and summer weather-related mortality need to be addressed (e.g., Frost and Auliciems 1993; Maarouf 1999). The real impact of air conditioning in mortality reduction is unknown, as is the quantification of the mortality displacement effect and acclimitization (e.g. Kalkstein 1993; Semenza et al. 1996; Kilbourne 1997). Finally, the use of more physiologically based comfort indices holds significant promise, particularly those that can be adapted to require inputs of less detailed weather parameters (e.g., Höppe 1999; Matzarakis et al. 1999; Lashewski and Jendritzky 2002).

Conclusions

Most models used to predict future weather-related mortality assume that the inherent relationship between the weather stressor and the mortality response is unchanged over time. Our research demonstrates that weather-mortality relationships have changed significantly in the United States between the 1960s and the 1990s. For the majority of the cities examined here, total mortality rates are less influenced by high apparent temperatures now than they were several decades ago. This muted mortality response is most apparent in northern or interior locations. By comparison, typically hot and humid southern cities exhibit little or no additional summer mortality for high T_a.

In most U.S. cities, a given incremental increase in T_a had less impact on total mortality in the 1990s than it did in the 1960s. Of the 28 largest cities in the United States, 22 either show no elevated mortality when T_a are high in the 1990s or statistically significant mortality declines in comparison to the 1960–1970s and/or 1980s. This result has profound implications on the accuracy of projections of future increases in heat-related mortality generated from global warming scenarios (Kalkstein and Greene 1997; Chestnut et al. 1998; NAST 2000). Until more accurate weather-mortality models are developed, it is necessary to adjust these mortality projections downwards in light of the observed decline in the sensitivity of the mortality of the U.S. population to high apparent temperatures.

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