Research | Article

Changing Heat-Related Mortality in the United States

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Heat is the primary weather-related cause of death in the United States. Increasing heat and humidity, at least partially related to anthropogenic climate change, suggest that a long-term increase in heat-related mortality could occur. We calculated the annual excess mortality on days when apparent temperatures—an index that combines air temperature and humidity—exceeded a threshold value for 28 major metropolitan areas in the United States from 1964 through 1998. Heat-related mortality rates declined significantly over time in 19 of the 28 cities. For the 28-city average, there were 41.0 ± 4.8 (mean ± SE) excess heat-related deaths per year (per standard million) in the 1960s and 1970s, 17.3 ± 2.7 in the 1980s, and 10.5 ± 2.0 in the 1990s. In the 1960s and 1970s, almost all study cities exhibited mortality significantly above normal on days with high apparent temperatures. During the 1980s, many cities, particularly those in the typically hot and humid southern United States, experienced no excess mortality. In the 1990s, this effect spread northward across interior cities. This systematic desensitization of the metropolitan populace to high heat and humidity over time can be attributed to a suite of technologic, infrastructural, and biophysical adaptations, including increased availability of air conditioning. *Key words:* air conditioning, apparent temperature, climate change, global warming, heat index, heat stress, human bioclimatology, human mortality, weather stress. *Environ Health Perspect* 111:1712–1718 (2003). doi:10.1289/ehp.6336 available via *http://dx.doi.org/* [Online 23 July 2003]

Heat waves are the most prominent cause of weather-related human mortality in the United States (Changnon et al. 1996). In northern U.S. cities, human mortality increases significantly on unusually hot and humid days (Bridger et al. 1976; Davis et al. 2002, 2003; Kalkstein and Davis 1989; Kalkstein and Greene 1997; Oechsli and Buechley 1970). Mortality increases are evident in total daily deaths as well as among the elderly subgroup (Applegate et al. 1981; Greenberg et al. 1983; Henschel et al. 1969; Jones et al. 1982; Kilbourne 1997; Kunst et al. 1993; Lye and Kamal 1977; Oechsli and Buechley 1970). Although a fraction of these deaths are directly attributable to heat, the majority are ascribed to causes of death not commonly considered to be weather related, such as circulatory and respiratory diseases (Bull and Morton 1978; Ellis et al. 1980; Keatinge et al. 1986; Larsen 1990a, 1990b). Increases in total and elderly mortality have also been associated with hot weather in Eurasia (Donaldson et al. 2003; Katsouyanni et al. 1993; Keatinge et al. 2000; Kunst et al. 1993; Laschewski and Jendritzky 2002; Nakai et al. 1999).

Atmospheric concentrations of human-produced greenhouse gases have increased significantly since the onset of the Industrial Revolution (Keeling and Whorf 1994). When the effects of the most important gases—carbon dioxide, methane, chlorofluorocarbons, ozone, and nitrous oxides—are combined, the current "effective" CO_2 concentration of approximately 450 ppm is more than 50% higher than the earth's natural, preindustrial

background level and represents a 30% increase since 1960 (Houghton et al. 1990, 1996, 2001). Evaluations of global surface temperature histories, after accounting for urban warming biases and other influences, indicate that the globe has warmed approximately 0.67°C since 1900 (Folland and Parker 1995; Jones 1994). Some scientists argue that this increase is directly attributable to increasing greenhouse gas levels (Arrhenius 1896; Hansen et al. 1998; Houghton et al. 2001; Manabe and Wetherald 1975). Furthermore, based upon scenarios of future increases in greenhouse gas emissions, climate models estimate a globally averaged temperature rise of 1.4–5.8°C between now and the year 2100 (Boer et al. 2000; Boville et al. 2001; Houghton et al. 2001; Mitchell and Johns 1997; Stouffer and Manabe 1999). In the United States, the air temperature has increased 1.0°C since 1964 (the first year in this analysis), and model projections suggest 3–5°C of warming by 2100 [National Assessment Synthesis Team (NAST) 2000].

Given the historic linkage between high temperatures and death, these climate model temperature projections have led scientists and public health officials to forecast significant increases in mortality from greenhouse warming in the United States in the early twenty-first century (Chestnut et al. 1998; Gaffen and Ross 1998; Kalkstein and Greene 1997; NAST 2000). The ultimate impact of climate change will depend upon the extent of biophysical adaptations and the implementation of effective and widely available countermeasures (Chestnut et al. 1998; Donaldson et al. 2003; Kalkstein and Greene 1997; Keatinge

et al. 2000; McGeehin and Mirabelli 2001; Seretakis et al. 1997). During the past several decades, the U.S. populace has been confronted with an increase in the annual number of heat-stress events, particularly in urban and suburban areas (Gaffen and Ross 1998). Projections of longer, more intense heat waves, more isolated hot days, higher minimum temperatures, and higher dew point temperatures arising from human influences on climate suggest a continuation of this trend. However, most, if not all, of the forecasts of increasing mortality are based on steady-state weather–mortality models that implicitly assume that weather–mortality relationships have not varied significantly over time. In contrast, we hypothesize here that mortality associated with warm and humid days has systemically declined over time (Davis et al. 2002, 2003; Donaldson et al. 2003).

The main purpose of this study was to determine if annual heat-related mortality rates have changed over the available period of record. This was accomplished by examining death rates on days in which, historically, the combination of high temperatures and humidity is correlated with significantly elevated mortality rates. Here, we explore temporal changes in the mortality characteristics of metropolitan area residents as a collective. Our specific goal was not to isolate the impact of heat alone, but to examine if, and the extent to which, the populace has adapted to increasing heat and humidity.

Materials and Methods

We examined daily mortality rates for 28 major U.S. cities over 29 years between 1964 and 1998. Raw mortality totals were culled

from the National Center for Health Statistics (1998) archives. These data include documentation on each death recorded in the United States as compiled from death certificates and include the date, place, and cause of death, and demographic factors such as the age, race, and sex of the decedent. Because few deaths are directly attributable to heat stroke and there has been no consistent standard in reporting heat-related mortality over our period of record (Ellis 1972; Ellis et al. 1980; Henschel et al. 1969), we use "all causes" mortality to include both heat stroke and any possible comorbid factors (Davis et al. 2002, 2003; Gover 1938; Kalkstein and Davis 1989; Kilbourne 1997; Kunst et al. 1993; Schuman 1972; Schuman et al. 1964). Over time, changes in the age structure of a city's population can significantly influence the daily mortality rate, thereby potentially biasing temporal comparisons. Furthermore, different cities have inherently different population demographics. To account for these variations both within and between cities over time, we standardized each day's mortality count relative to a hypothetical standard city with a population of 1 million people. The demographics of this standard city were based on the age distribution of the entire U.S. populace in the year 2000. We age-adjusted our data using the direct standardization method (Anderson and Rosenberg 1998). County-level population data were acquired from U.S. Census sources for 1960, 1970, 1980, 1990, and 2000 for 10 age classes (U.S. Department of Commerce 1973, 1982, 1992, 2001), and the population of intervening years was estimated via linear interpolation.

To examine temporal changes in heat-related mortality, we divided the time series into three "decades" of approximately equal length [1964–1966 and 1973–1979 (1960s–1970s), 1980–1989, 1990–1998]. Data from 1967–1972 were not used for this study because the date of death was not systematically reported, thereby requiring the exclusion of those years.

In our analysis we used large metropolitan areas with enough daily deaths to generate robust statistical samples. We used the 1990 definitions of the counties that comprised each metropolitan statistical area (MSA) and U.S. Census data to define the population of each city. For example, according to the 1990 MSA definition, Chicago, Illinois, comprised Cook, Du Page, and McHenry Counties. Urbanization has resulted in the addition of counties to some official MSA definitions over time, so rural counties not officially designated within an MSA in the 1960s, for example, were nevertheless included in our analysis to maintain temporal sampling consistency.

Weather varies significantly on a daily basis throughout most of the United States; therefore, proper analysis of weather–mortality relationships requires the use of daily mortality records linked to a representative weather observation site. Daily weather records were retrieved for the same 28 cities from a proximate U.S. National Weather Service observation station within each metropolitan area (Table 1). Because our analysis required hourly observations, only first-order observation stations could be used, which limited our station choice to only a single station within most of the MSAs.

Using energy balance principles, Steadman (1979, 1984) demonstrated that humans respond physiologically not only to temperature but to a combination of temperature and humidity, among other factors. Biometeorologists have therefore developed a variety of indices of atmospheric conditions in an effort to determine how humans react to environmental stressors (e.g., Gagge et al. 1986; Greenberg et al. 1983; Höppe 1993, 1999; Horikoshi et al. 1997; Jendritzky and Nübler 1981; Jendritzky et al. 2000). One such measure, the apparent temperature (AT) (Steadman 1979, 1984), combines air temperature and humidity into a single variable. This index of the relative "sultriness" of the air serves as the basis for the heat index, the most commonly used summer discomfort measure in the United States, which serves as one of the bases of the heat advisories issued by the U.S. National Weather Service.

In an effort to determine the weather variables most closely linked to high mortality, we plotted daily mortality rates versus several weather variables, including morning and afternoon air temperature, dew point temperature (a measure of the amount of moisture in the air), and AT for six representative MSAs in different climatic regions. In general, the strongest relationships were found with afternoon AT, although the results were similar using morning dew point temperature, in agreement with previous research (Kalkstein and Davis 1989; Smoyer et al. 2000). Therefore, we chose afternoon AT as the independent variable in this analysis. Hourly weather data were obtained for each city [National Climatic Data Center (NCDC) 1993; National Environmental Satellite, Data, and Information Service 2000], and data were extracted for 1600 hr local standard time (LST), approximating the time of daily maximum AT.

There is often a lag between the mortality response and a given weather event (Bull and Morton 1978; Gorjanc et al. 1999; Kalkstein and Davis 1989; Rogot and Padgett 1976). After exploring several possible lags (from 0 to 3 days), we used a 1-day lag throughout this study because this consistently provides the strongest relationship between weather and mortality.

In the United States and other countries, mortality is higher in winter than in summer (Donaldson and Keatinge 1997; Eurowinter Group 1997; Langford and Bentham 1995; Laschewski and Jendritzky 2002; Lerchl 1998). This inherent seasonality could bias an analysis of heat-related mortality. For example, an early- or late-season heat wave (in April or October) could be linked with anomalously high mortality counts relative to mid-summer simply because death rates are generally higher

Table 1. Meteorological stations associated with each MSA.

Abbreviation	MSA	Meteorological station	WBAN no.[a]
ATL	Atlanta, Georgia	Atlanta Hartsfield International Airport	13874
BAL	Baltimore, Maryland	Baltimore–Washington International Airport	93721
BOS	Boston, Massachusetts/New Hampshire	Boston Logan International Airport	14739
BUF	Buffalo, New York	Buffalo Niagara International Airport	14733
CHI	Chicago, Illinois	Chicago O'Hare International Airport	94846
CHL	Charlotte, North Carolina	Charlotte Douglas International Airport	13881
CIN	Cincinnati, Ohio/Kentucky/Indiana	Cincinnati Northern Kentucky Airport	93814
CLE	Cleveland, Ohio	Cleveland Hopkins International Airport	14820
DAL	Dallas, Texas	Dallas–Fort Worth International Airport	03927
DEN	Denver, Colorado	Denver Stapleton International Airport/ Denver International Airport	23062
DET	Detroit, Michigan	Detroit Metropolitan Airport	94847
HOU	Houston, Texas	Houston Bush Intercontinental Airport	12960
KSC	Kansas City, Missouri/Kansas	Kansas City International Airport	03947
LAX	Los Angeles, California	Los Angeles International Airport	23174
MIA	Miami, Florida	Miami International Airport	12839
MIN	Minneapolis, Minnesota/Wisconsin	Minneapolis–St. Paul International Airport	14922
NEW	New Orleans, Louisiana	New Orleans International Airport	12916
NYC	New York, New York	New York Laguardia Airport	14732
NFK	Norfolk, Virginia	Norfolk International Airport	13737
PHI	Philadelphia, Pennsylvania/New Jersey	Philadelphia International Airport	13739
PHX	Phoenix, Arizona	Phoenix Sky Harbor International Airport	23183
PIT	Pittsburgh, Pennsylvania	Pittsburgh International Airport	94823
POR	Portland, Oregon/Washington	Portland International Airport	24229
SEA	Seattle, Washington	Seattle–Tacoma International Airport	24233
SFC	San Francisco, California	San Francisco International Airport	23234
STL	St. Louis, Missouri/Illinois	St. Louis Lambert International Airport	13994
TAM	Tampa, Florida	Tampa International Airport	12842
WDC	Washington DC/Maryland/Virginia/ West Virginia	Washington Reagan National Airport	13743

[a]Weather-Bureau-Army-Navy number.

in April and October. To remove this inherent seasonal cycle in mortality and produce a stable baseline for comparisons, we converted the data from daily mortality totals into daily mortality anomalies by subtracting from each day's mortality count the median mortality for the month in which the deaths occurred. We used the monthly median rather than the mean because the daily frequency distribution is often nonnormal, especially in months with several high mortality days. Through this technique, we enhanced the possibility of identifying relationships between daily ATs and daily mortality. Furthermore, by generating monthly mortality anomalies, we effectively standardized our dependent variable by removing the long-term trend of declining death rates, thus facilitating comparisons of heat-related mortality between decades.

Plots of daily mortality versus temperature indicate that death rates increase near the extremes of the temperature distribution in most cities with temperate climates (Alderson 1985; Bull 1973; Bull and Morton 1978; Curwen 1991; Kalkstein and Davis 1989; Khaw 1995; Kunst et al. 1993; McKee 1990; Rogot and Padgett 1976; Wyndham and Fellingham 1978). This observation led Kalkstein and Davis (1989) to propose the concept of a "threshold temperature," or the air temperature beyond which mortality increases above the baseline level, for either warm-season or cold-season mortality. Examination of mortality on the subset of days with ATs beyond this threshold enhanced our ability to link mortality to daily weather parameters. Our emphasis in this analysis was on warm-season mortality, so we only calculated thresholds at the high end of the AT distribution.

Specifically, we define a "threshold AT" as the AT at and above which mortality rates are significantly higher than the baseline rate (which is zero for deseasoned data). We aggregated the daily mortality anomalies into overlapping 2°C AT class intervals. When the mean class mortality anomaly exceeded zero based on a one-sample, one-tailed t-test ($\alpha \leq 0.05$) and remained elevated for all higher ATs, the mean AT within the lowest class with significantly above-normal mortality was defined as the threshold AT. For example, Figure 1A shows the relationship between daily all-causes mortality and 1600 hr LST AT for Chicago during the 1960s–1970s decade. Although in general there is no relationship between these variables, there is an apparent increase in mortality at high ATs. This is made more evident by computing the mean mortality within overlapping 2°C AT interval widths (Figure 1B). Because mortality increases significantly for ATs at and above 30°C, this value is calculated as the threshold AT for Chicago for the 1960s–1970s decade.

For each city, the death rates for all days above the threshold AT were summed by decade and then averaged to generate an MSA-specific decadal mean annual value. This excess mortality above the baseline approximates "heat-related" mortality rates for weather events in which the threshold AT is equaled or exceeded. Annual excess deaths were compared across decades based on bootstrapped estimates of the standard deviation for each city and decade. Bootstrapping is a nonparametric statistical procedure by which robust parameter estimates can be obtained from relatively small data samples (Efron and Gong 1983). Frequency distributions of a parameter are generated by randomly selecting observations from a sample, with replacement, multiple times. In our case, each standard deviation was estimated using 10,000 replicates, and determinations of statistically significant differences across decades were based on confidence bands defined by two standard deviations from the mean (Wilks 1995).

In previous work (Davis et al. 2002, 2003), we used a constant threshold AT for each city, defined in the 1960s and 1970s "decade" as a baseline, to determine if weather–mortality relationships had changed over time. But in this research, we employed a threshold AT that varies by decade. The resulting estimate of excess mortality should thus represent the average annual number of heat-related deaths per MSA within each decade. Ideally, one might hope to allow the threshold AT to vary from year to year; however, sample size and statistical robustness considerations, arising from the lack of warm and humid days in some years and locations, make an annual threshold calculation difficult and necessitate aggregation, which we chose to use at the decadal scale.

Temporal variations in excess deaths related to heat can arise from a number of factors, one of which is a changing climate that could influence exposure rates. To examine background climate change and related heat stress, annual trends in summer (June, July, and August) 1600 hr LST ATs were calculated for each city using least-squares linear regression. Statistical significance is based on a 0.05 α level.

Results

Heat-related mortality has consistently declined on a decadal basis (Figure 2). In 19 of our 28 study cities, total annual heat-related (population-adjusted) mortality was statistically significantly lower in the 1990s than in our 1960s–1970s decade. On average, for the 28 cities, the number of excess deaths on hot and humid days declined from 41.0 ± 4.8 deaths/city/year (mean ± SE) in the 1960s–1970s, to 17.3 ± 2.7 in the 1980s, to only 10.5 ± 2.0 in the 1990s. Because 12 of the 28 cities showed no evidence of the existence of a threshold AT in the 1990s, mortality rates in these locations were unrelated to high ATs despite a widespread increase in summer ATs (Gaffen and Ross 1998).

The temporal and spatial patterns of excess deaths merit some attention. In the 1960s–1970s, every MSA except Tampa, Florida, exhibited statistically elevated mortality on hot and humid days. By the end of the 1980s, 6 of the 28 MSAs had no threshold AT (and thus no excess deaths), and an additional 11 locations showed statistically significant mortality declines relative to the 1960s–1970s. Thus, by the 1980s, mortality rates declined in 41% of the cities that had elevated mortality one "decade" earlier. Most of the cities with no elevated mortality in the 1980s are in the southern United States (Phoenix, AZ, Houston, TX, Miami, FL, Charlotte, NC, Norfolk, VA)—with Denver, Colorado, being the exception. Most of the cities with significant declines by the 1980s but with elevated death rates are in the northeastern quadrant of the United States. Through the 1990s, the general trend toward lower mortality rates continued. Dallas, Texas; Minneapolis, Minnesota; Kansas City, Missouri; St. Louis, Missouri; Cincinnati, Ohio; and Washington, DC, all exhibited no elevated death rates on high AT days in the 1990s, whereas deaths in Baltimore, Maryland, declined relative to the 1980s but remained significantly elevated. Therefore, by the end of our period of record,
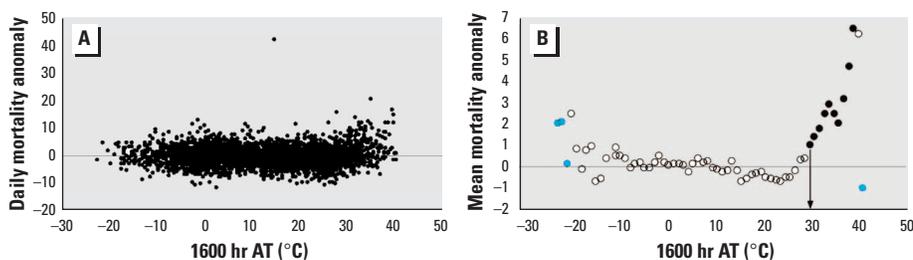
Figure 1. (*A*) Daily mortality anomalies versus 1600 hr LST AT for Chicago, Illinois, 1964–1966 and 1973–1979; the daily mortality outlier in the middle of the temperature range is associated with an airliner accident in 1979. (*B*) The mean daily mortality for overlapping 2°C AT class intervals; the threshold AT is 30°C—the average AT within the lowest AT class above which mortality is statistically significantly elevated. Open circles indicate class intervals in which the mean mortality anomaly is significantly greater than zero. Blue circles represent class intervals with five or fewer samples.

12 of the 28 MSAs had no excess deaths linked to high ATs.

In general, cities along the southern tier of the United States, particularly in the Southeast, exhibited the weakest heat–mortality relationships. Most MSAs in the Northeast and Great Lakes regions have had mortality declines over time but still showed statistically significant mortality increases after high AT days in the 1990s. By contrast, none of the West Coast cities have seen significant mortality declines; in fact, excess death rates in Seattle, Washington, have actually increased compared with the 1960s–1970s. A few other locations exhibit mortality patterns that are outliers relative to neighboring cities, such as New Orleans, Louisiana; Atlanta, Georgia; and Buffalo, New York, where the decadal death rates are more comparable with West Coast locales.

Summertime trends in 1600 hr LST ATs from 1964–1998 exhibit statistically significant increases in 9 of the 28 cities (Figure 3). These increases, which can arise from a combination of higher temperatures and/or increasing humidity (Gaffen and Ross 1998, 1999; Knappenberger et al. 1996; Robinson 2000; Schwartzman et al. 1998), are concentrated in the southern United States. However, isolated increasing trends are also evident outside of this general region in San Francisco, California, and New York, New York. Of the remaining 19 MSAs, there is a general tendency toward higher ATs over time, although the regression slopes are not statistically significant and therefore are indistinguishable from no long-term change. Only two stations, Minneapolis and Kansas City, have decreasing summer ATs, and neither decline is significant. Given the general trend toward temporally increasing heat and humidity across most U.S. metropolitan areas, one would expect increasing heat stress to exposed individuals over time. This expectation should be tempered by regional adaptations in which individuals attempt to limit their exposure to high heat and humidity, so the number of exposed individuals should vary over time and space.

A comparison of the interactions between AT trends and mortality shows little overall pattern (Table 2). Of the nine MSAs with significantly increasing summer ATs, six had statistically significant mortality declines in the 1990s (relative to the 1960s–1970s), two showed no change (Atlanta and San Francisco), and one had no AT–mortality relationship over the entire period of record despite significantly increasing heat stress (Tampa). Both of the MSAs with declining ATs also exhibited mortality declines (Minneapolis and Kansas City).

Discussion

Reductions in weather-related mortality over time and regional differences in mortality responses are related to several factors. Health care has continued to improve significantly since the 1960s owing to advances in medical knowledge (Goldman and Cook 1984; Seretakis et al. 1997). Urban planners and architects have increasingly factored summer relief from heat stress into their designs, including more shaded outdoor areas and ready access to potable water. Public health officials, government agencies, and the media have taken more proactive measures to address potential mortality threats on unusually hot and humid days, including the recent implementation of heat watch–warning systems (Kalkstein et al. 1996; McGeehin and Mirabelli 2001). Furthermore, human biophysical acclimatization to high temperatures could also play a role in reduced mortality, both within season (Greenberg et al. 1983;
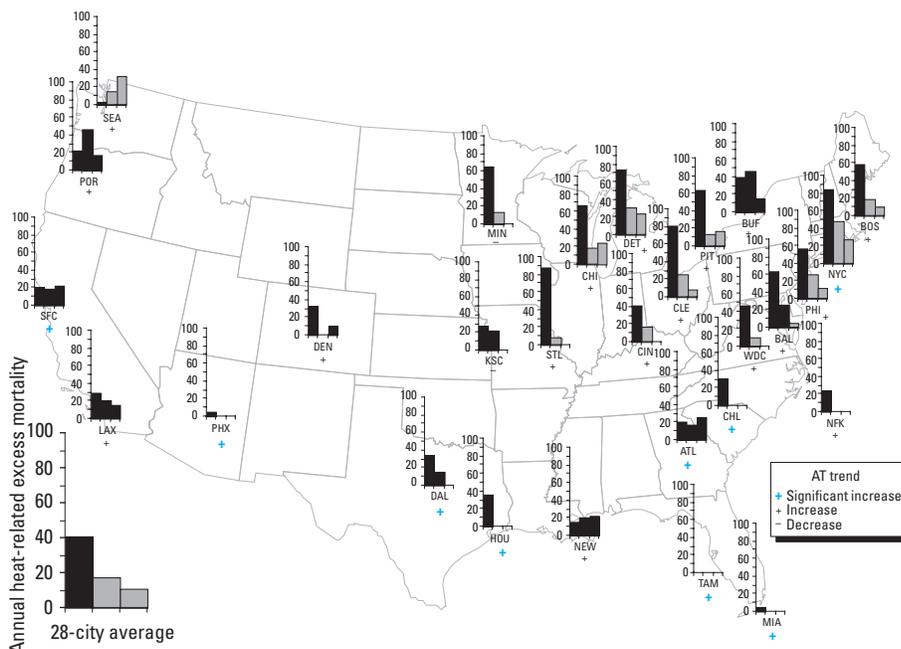
Figure 2. Annual heat-related mortality rates (excess deaths per standard million population on days in which the decadal-varying threshold AT is equaled or exceeded) by city and decade, and long-term trend in summer afternoon AT. Each histogram bar indicates a different decade: from left to right, 1960s–1970s, 1980–1989, and 1990–1998. Decades without histogram bars exhibit no threshold ATs and no heat-related mortality. Decades with gray bars have mortality rates that are statistically significantly different from the decades indicated by black bars. The average excess deaths across all 28 cities is shown at the lower left. AT trends (Figure 3) are indicated beneath each city abbreviation (defined in Table 1).
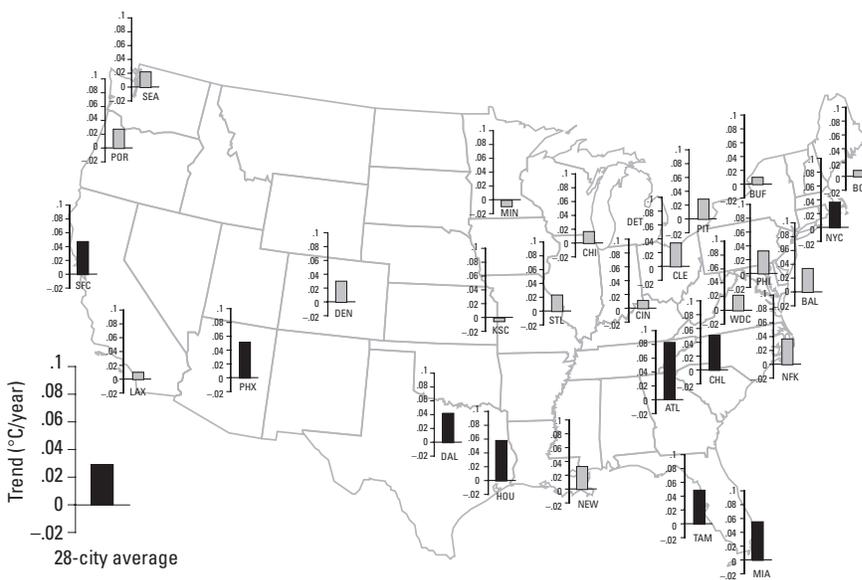
Figure 3. Map of average summer (June, July, August) 1600 hr LST AT trends (°C/year) for 1964–1998. Black bars indicate statistical significance ($p \leq 0.05$). City abbreviations are defined in Table 1.

Kalkstein 1993; Marmor 1975; Seretakis et al. 1997) and over longer periods of time (Bonner et al. 1976; Frost and Auliciems 1993; Keatinge et al. 2000; Wyndham et al. 1976).

It is likely that air conditioning has been a critical factor in reducing heat-related mortality. Air conditioning has permeated many businesses, automobiles, and households over the last 20 years, especially in cooler regions where it had once been considered more of a luxury than a necessity (McGeehin and Mirabelli 2001). To date, it has been difficult to quantify the role of air conditioning in reducing mortality because of multiple, confounding factors. In one case–control study, Kilbourne et al. (1982) determined that access to air conditioning reduced heat stroke by 400%. In a large cohort study comparing households with and without air conditioning in the early 1980s, Rogot et al. (1992) identified a 42% lower death rate for air-conditioned households during hot months. Kalkstein (1993) estimated the impact of air conditioning by comparing mortality trends on days with "offensive" air masses (high mortality days in which air conditioning use would be maximum) versus all other days. For New York City, Kalkstein estimated a 21% reduction in mortality resulting from air conditioning use. Separate analyses of the impact of air conditioning on mortality during the 1995 Chicago heat wave indicate that moving from unventilated, indoor locations to air conditioning reduced the mortality risk of individuals by a factor of about 5–6 (Chan et al. 2001; Semenza et al. 1996). Although there is little disagreement that air conditioning reduces summer mortality rates, estimates of the actual impact on mortality rates vary markedly.

To examine the impact of air conditioning availability in more detail, we used data on the percentage of households with available air conditioners according to the Energy Information Agency (2003) for the years 1980, 1981, 1982, 1984, 1987, 1990, 1993, and 1997. Data on air conditioner use are available for nine census divisions covering the United States. We averaged the data from the available years within the period 1980–1989 and 1990–1998 to produce decadal mean values of air conditioner use within each of the nine regions. We compared these values with

the annual excess heat-related mortality data for these two decades averaged across all of the MSAs within eight of the nine census regions (there were no cities with one of the regions).

In all regions except one, the mortality decline from the 1980s to the 1990s was coupled with increased air-conditioning penetration (Figure 4). The lone exception is the Mountain region, which includes the climatically dissimilar MSAs of Phoenix and Denver, each of which exhibited much different decadal mortality trends. Excluding the Mountain region, on average for U.S. cities, excess mortality was reduced by 1.14 deaths/year (per standard million) for every percentage increase in home air conditioning availability. Overall, there is a fairly strong inverse relationship between air conditioning and mortality rates. Air conditioning saturation is almost complete in the West South Central, South Atlantic, and West North Central regions, where 10 of the 13 cities exhibited no threshold ATs in the 1990s. Mortality rates were highest in the Pacific and Northeast regions where air conditioning use has become more commonplace only recently. Given this general relationship, one would anticipate significant mortality declines until the time when 100% air-conditioning saturation is approached for the entire United States. Afterward, the net impacts of high heat and humidity on mortality remain an open question. But contemporary analyses should focus on cities in the southern U.S. regions where air conditioning is present in most homes. The impacts of heat waves on mortality there may provide some case studies of how future populations might respond to heat stress events under full air-conditioning saturation conditions.

This cursory analysis implicitly assumes that air conditioning completely accounts for the observed mortality changes. In this article, our goal is not to attribute the observed declines in heat-related deaths to specific causes. Air conditioning is one of the major factors, but other technologic and biophysical changes, including those outlined earlier in this discussion, will most likely have some influence as well.

There is evidence of an adaptation response in the spatial patterns of mortality declines. In the 1980s, most of the cities with no elevated

mortality were in the southern United States where high summertime heat and humidity are common; for example, there was a lack of excess mortality in Phoenix and Houston, where temperatures and ATs can often reach very high levels. Apparently, the populace in and around these cities has largely adapted to these uncomfortable conditions, no doubt by incorporating a combination of the factors cited above. Through the 1990s, cities with no identifiable threshold ATs included several midwestern cities that were weather sensitive one decade earlier. This pattern suggests that adaptations to heat and humidity originally seen in the southeastern United States have spread northward (Davis et al. 2003). In effect, the mortality response in northern cities in the 1990s has become more like that seen in southern cities in the 1980s. The lack of mortality declines in the western United States, where ATs typically do not reach uncomfortable levels, remains a mystery. Possible confounding factors include the representativeness of the weather observation sites in MSAs that encompass mountainous terrain, changing demographics related to rapid immigration, and air quality impacts (Davis et al. 2003). It is perhaps noteworthy that the Pacific Coast and Mountain regions have the lowest percentage of residential air conditioning availability in the United States (Figure 4). Resolution of the western U.S. AT–mortality relationships remains a topic for future investigation.

Our analysis has not addressed the mortality impacts of weather variability. One current hypothesis is that individuals are stressed during the summer by significant temperature changes, particularly minimum temperatures. High minimum temperature variability has been linked to higher mortality rates in northeastern and northern interior cities (Chestnut
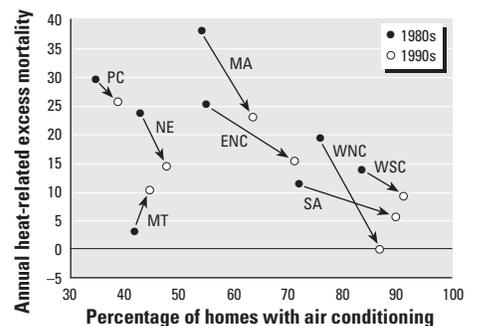
Figure 4. Excess annual heat-related mortality (per standard million), averaged for the MSAs within U.S. regions, versus the average percentage of homes with air conditioning, for the 1980s and 1990s. Abbreviations: ENC, East North Central (CHI, DET, CLE, CIN); MA, Mid-Atlantic (NYC, BUF, PHI, PIT); MT, Mountain (DEN, PHX); NE, Northeast (BOS); PC, Pacific (SEA, POR, SFC, LAX); SA, South Atlantic (BAL, WDC, NFK, CHL, ATL, TAM, MIA); WCS, West South Central (DAL, HOU, NEW); WNC, West North Central (MIN, KSC, STL); MSA abbreviations are listed in Table 1.

Table 2. Relationship between AT trends and mortality changes: 1980s versus 1960s–1970s and 1990s versus 1960s–1970s.

		1960s–1970s vs. 1980s			1960s–1970s vs. 1990s		
	AT trend	Significant mortality decline	Still significantly elevated	Neither	Significant mortality decline	Still significantly elevated	Neither
Significant increase	9	5	3	1	6	2	1
Increase	17	11	6	0	11	6	0
Decrease	2	1	1	0	2	0	0
Significant decrease	0	0	0	0	0	0	0

Numbers represent the station count within each category.

et al. 1998; Kalkstein 1993, 2000). This observation could partially account for the spatial pattern of decadal mortality declines across the United States, because mortality rates in the 1990s remain elevated in the Northeast and West Coast, where summer temperature variability typically is higher because of air mass changes associated with more frequent frontal passages. In an effort to provide a cursory examination of possible impacts of variability on our observed mortality declines, we calculated the trends in the summer (June, July, and August average) 1600 hr LST AT standard deviation from 1964 through 1998. Only 3 of our 28 MSAs exhibited statistically significant ($p \leq 0.05$) trends, and the directions of the trends were inconsistent (increasing variability in Houston and New Orleans; declining variability in Minneapolis). Our findings indicate that temporal changes in variability have played little role in the observed mortality declines. With respect to possible future changes in temperature variability that might result from a warming climate, Robeson (2002) examined the relationship between mean air temperature and air temperature variance across the United States. In general, Robeson found increasing temperatures to be associated with reduced temperature variance. In the summer, this relationship is statistically significant for minimum temperatures in the southeastern quarter of the United States and for maximum temperatures in the western interior regions. Very few significant positive mean–variance relationships were observed. These results suggest that, given a background warming, air temperature variance should generally decline across the United States, a hypothesis supported by Michaels et al. (1998) in their analysis of July maximum and minimum temperatures. However, the fundamental question of the differential mortality impact of prolonged exposure to high heat and humidity compared with highly variable weather conditions remains unresolved.

Finally, there appears to be no relationship between temporal climate trends in AT and mortality responses (Table 2). This calls into question the utility of efforts linking climate change forecasts to future mortality responses in the United States (Chestnut et al. 1998; Kalkstein and Greene 1997; NAST 2000). Most of these and similar projections implicitly assume that the historical relationship between AT and mortality is constant. However, this and related research suggest that adaptations (in all forms) preclude the assumption of a stationary time series; therefore, any projections of future mortality rates linked to climate change must explicitly account for temporal changes in heat-related death rates (Davis et al. 2002, 2003). We intentionally did not attempt to account for temporal changes in the urban heat island, as

is common in many climatological studies. We hoped to use ATs that were representative of the ambient conditions experienced by the populace within each MSA. The observed trends in AT (Figure 2) are likely related to a variety of causes, including increasing greenhouse gas levels, urbanization effects, land use changes, and simple natural climate variability. Regardless of the cause of the observed changes in background heat and humidity, the pattern of changes is unrelated to the observed reductions in mortality.

Conclusions

In general, over the past 35 years, the U.S. populace has become systematically less affected by hot and humid weather conditions. All-causes mortality during heat stress events has declined despite increasingly stressful weather conditions in many urban and suburban areas. This relative "desensitization" of the U.S. metropolitan populace to weather-related heat stress can be attributed to a variety of factors, including improved medical care, infiltration of air conditioning, better public awareness programs relating the potential dangers of heat stress, and both human biophysical and infrastructural adaptations. Thus, heat-related mortality in the United States seems to be largely preventable at present (McGeehin and Mirabelli 2001; Semenza et al. 1996). Public health officials and primary care physicians should warn their patients of the dangers associated with high heat and humidity. This is particularly true for the most susceptible groups, which include the elderly and individuals being treated for circulatory and respiratory conditions, diseases that have the highest mortality rates.

With respect to projections of future heat-related mortality that might arise from greenhouse-gas–induced warming, urban warming, or other factors, it is clear that these projections must incorporate the observed reductions in heat vulnerability. However, many questions remain with respect to future heat-mortality impacts. If air conditioning is indeed the main cause of the observed declines, once air conditioning penetration approaches market saturation, will a significant heat-mortality impact remain in the United States? Will air conditioning availability extend to all socioeconomic classes? What is the impact of cheap energy on air conditioning use, and will future changes in energy markets and pricing inadvertently encourage people to endanger themselves during heat waves? In addition, the role of human biophysical adaptations to changing climates should be considered. One current hypothesis is that residents in the Northeast are less acclimatized to summer heat and humidity because of its lack of persistence, compared with southern cities, where summer thermal variability is low. At present, future temperature variability

is difficult to predict, but it could impact mortality rates. Current research suggests that, in most of the United States, summer variability should decline as temperatures increase. But overall, it is obvious that there is no simple association between increased heat wave duration or intensity and higher mortality rates in the United States.

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