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Modifiers of the Temperature and Mortality Association in Seven US Cities

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This paper examines effect modification of heat- and cold-related mortality in seven US cities in 1986–1993. City-specific Poisson regression analyses of daily noninjury mortality were fit with predictors of mean daily apparent temperature (a construct reflecting physiologic effects of temperature and humidity), time, barometric pressure, day of the week, and particulate matter less than 10 µm in aerodynamic diameter. Percentage change in mortality was calculated at 29°C apparent temperature (lag 0) and at –5°C (mean of lags 1, 2, and 3) relative to 15°C. Separate models were fit to death counts stratified by age, race, gender, education, and place of death. Effect estimates were combined across cities, treating city as a random effect. Deaths among Blacks compared with Whites, deaths among the less educated, and deaths outside a hospital were more strongly associated with hot and cold temperatures, but gender made no difference. Stronger cold associations were found for those less than age 65 years, but heat effects did not vary by age. The strongest effect modifier was place of death for heat, with out-of-hospital effects more than five times greater than in-hospital deaths, supporting the biologic plausibility of the associations. Place of death, race, and educational attainment indicate vulnerability to temperature-related mortality, reflecting inequities in health impacts related to climate change.

climate; education; ethnic groups; heat; mortality; poverty; socioeconomic factors; weather

Abbreviation: PM_{10}, particulate matter less than 10 µm in aerodynamic diameter.

Climatic changes resulting from human activities are projected to increase overall average temperatures as well as extreme weather events across the globe, among other effects (1–3). Efforts to describe and quantify the impacts of these changes provide information for policy makers considering the costs and benefits of controlling greenhouse gas emissions. Health effects in humans are one important area for study, and the literature and interest in this area are growing (4–8). The influence of thermal stress on morbidity and mortality is considered a direct health impact, quantifiable in epidemiology studies (9, 10). Because global warming is likely to increase average temperatures, a focus of this research has been on the effects of heat waves (11, 12). In fact, the projected rise in global temperatures may be of benefit in colder climates where there is a strong wintertime cold effect (13). Overall, however, the net effect of climate change is expected to be an increase in weather-related mortality (14).

Extreme temperatures are associated with increased daily mortality in numerous regions of the world; generally, nonlinear relations (U, J, or V shaped) have been observed with increased mortality at high or low temperatures (15, 16). Mortality has also been found to increase during periods of 3 or more days of unusual temperatures in summer or winter, showing that temperature variability is an important determinant of human health effects (17). A recent study of 12 US cities explicitly evaluated the variance of summertime temperature as a modifier of the effects of hot days and found effect modification for all-cause mortality (15). Similarly, the variance of wintertime temperature modified the effect of very cold days on respiratory mortality (18). Cold-related mortality has been observed to be higher than heat-related mortality in some European countries (19). Heat-related mortality is more likely to occur in areas where extreme heat occurs infrequently, because populations are hypothesized to be less-well adapted to these high temperatures (20).

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To develop public health policies that protect those persons most vulnerable to temperature extremes, researchers have identified factors that confer susceptibility and have called for further research in this area (21, 22). The purpose of this study was to evaluate additional factors that may affect the temperature and mortality relation in seven US cities while controlling for the effects of air pollution. Although almost all studies that examine the effects of air pollution and daily deaths have controlled for weather, control for air pollution in studies assessing the effects of weather has been rare.

MATERIALS AND METHODS

Data sources

The authors used information from Denver, Colorado; Detroit, Michigan; Minneapolis and St. Paul, Minnesota (referred to as "Minneapolis" in this paper); New Haven, Connecticut; and Pittsburgh, Pennsylvania (for 1986–1993); and Chicago, Illinois, and Seattle, Washington (for 1988–1993). For all these cities, data on particulate matter less than 10 μm in aerodynamic diameter (PM_{10}) were available for the time period of interest, although there were some gaps in the pollution data for Denver and New Haven. Control for PM_{10} was desired, because it has been associated with daily mortality in many studies. Data were obtained from the counties corresponding to the metropolitan areas; more detail on this process is given elsewhere (23).

Meteorologic measurements were obtained from the airport weather station nearest to each county, including daily mean temperature, relative humidity, and barometric pressure (EarthInfo CD NCDC Surface Airways, EarthInfo Inc., Boulder, Colorado). Barometric pressure has been associated with changes in oxygen saturation and pulse rate in elderly subjects (24) as well as with daily mortality (25, 26) and hence was chosen as a control variable. An index of human discomfort, apparent temperature (AT), defined as a person's perceived air temperature, was calculated by using the following formula (27, 28): $AT = -2.653 + (0.994 \times Ta) + (0.0153 \times Td^2)$, where Ta is air temperature and Td is dew point temperature. Because mean daily temperatures never exceeded 34°C, a wind-speed correction was not required (28).

The US Environmental Protection Agency's Aerometric Information Retrieval Service monitoring network provided PM_{10} data, and an algorithm was adopted so that all available data from multiple monitors across the city could be used while accounting for different means and standard deviations among these monitors, as described in previous work (29). For Denver and New Haven, horizontal visibility and other meteorologic data from the EarthInfo database, and PM_{10} before and after days for which values were missing from the Aerometric Information Retrieval Service database, were used to impute the missing values of PM_{10}.

Daily mortality data were extracted from the National Center for Health Statistics mortality tapes, and deaths from external causes (*International Classification of Diseases*, Ninth Revision codes 800–999) were excluded. Separate *stratified* data sets were created with death counts by gender, age (less than 65 years, 65 years or older), race (Black, White), education (high school education or less, any post-high school education), and place of death (outside or in a hospital). These potential effect modifiers were chosen because previous analyses showed that temperature effects differed according to gender, age, and race (22, 30–32). Education is a commonly used indicator of socioeconomic position, and place of death was of interest because people who died in a hospital were more likely to be in an air-conditioned or heated environment and hence less likely to experience ambient temperature conditions. Location of death in a hospital may also reflect whether the decedent had health insurance and the nature of the illness leading to death (sudden vs. prolonged). Racial classifications other than Black or White represented 4.5 percent of the deaths in Seattle, 2 percent or less of the deaths in Denver and Minneapolis, 1 percent of the deaths in Chicago, and less than 1 percent of the deaths in the three other municipalities and were not included in the stratified analysis. Educational level was available from 1990 to 1993 only, but the other categories were recorded on the death certificates for the entire study period. During 1986–1993, a total of 867,257 people died in all seven metropolitan areas. An additional analysis was performed that examined cardiovascular- (*International Classification of Diseases*, Ninth Revision codes 390–429) and respiratory- (codes 460–519) cause mortality for Chicago in relation to age, race, and place of death.

Statistical methods

The statistical models were Poisson regression analyses with daily death counts as the dependent variable. Because some of the predictor variables are not likely to have a linear association with daily deaths, natural cubic splines (33) were used to model these relations. In spline models, separate polynomial functions are fit to different ranges of a predictor and constrained to meet the boundary points (called knots) between the regions (34). A natural cubic spline, which fits a linear function after the knots at either end of the spline, was specified (35). Independent variables included the mean of PM_{10} on the day of death and the previous day, modeled as a linear term, and natural splines to model mean daily barometric pressure and apparent temperature, day of the week, and day of study (to control for long-term and seasonal trends). The model was of the following form, where $E(Y)$ is the expected daily death count, β is the coefficient of the linear predictor(s), and NS is the natural spline function for the nonlinear terms; only one of each type of predictor is shown: $\log[E(Y)] = \alpha + \beta \times \text{(linear predictor)} + \text{NS} \times \text{(nonlinear predictor)}$.

A recent analysis examined the lag structure of the weather and daily mortality association in 12 US cities, finding that the cold temperature effect persisted for days but that hot temperature effects were shorter term (lags 0 and 1 predominately) (15). That study used distributed lag models (26) to evaluate whether the observed effects were mostly due to deaths being brought forward by just a few days (harvesting) or whether the temperature effects were longer term. In light of these results, we chose to model the effects of heat and cold with two different terms in the regression models: 1)

TABLE 1. Descriptive statistics for total mortality and mean and range (in parentheses) of environmental variables in 1986–1993 for all US study cities except Chicago and Seattle (1988–1993)

	Mortality (no. of deaths)	Apparent temperature* (°C)	Barometric pressure (inches Hg†)	PM_{10}‡
Chicago, Illinois	292,195	9.3 (–13.2, 36.9)	29.3 (28.5, 30.1)	36.3 (–1.2, 197.4)
Denver, Colorado	36,717	8.6 (–15.2, 27.7)	24.7 (24.1, 25.1)	36.3 (–11.5, 132.7)
Detroit, Michigan	174,523	9.3 (–13.6, 36.2)	29.3 (28.5, 30.1)	36.6 (–1.8, 132.0)
Minneapolis, Minnesota§	94,252	7.4 (–14.6, 36.9)	29.1 (28.4, 30.0)	28.1(–0.8, 150.6)
New Haven, Connecticut	60,153	9.6 (–11.2, 36.3)	29.8 (29.0, 30.6)	29.0 (–3.0, 92.9)
Pittsburgh, Pennsylvania	123,877	10.3 (–12.7, 34.3)	28.7 (27.8, 29.4)	36.0 (–3.2, 145.9)
Seattle, Washington	85,540	9.8 (–8.1, 27.3)	29.6 (28.6, 30.1)	32.2 (–5.2, 32.2)

* Defined as a person's perceived air temperature.

† One inch Hg = 25.4 mmHg.

‡ PM_{10}, particulate matter less than 10 μm in aerodynamic diameter (μg/m^3).

§ Also includes St. Paul.

mean daily apparent temperature at lag 0 (i.e., the day of death) was used to model the heat effect and 2) the average mean daily apparent temperature for the 3 days preceding the day of death (lags 1, 2, and 3) was used to represent the cold effect. Because our models stratified on a number of potential effect modifiers per city, the mean daily counts in each stratum were sometimes small. The distributed lag model yielded unstable results for some cities, so that approach was not used. The heat and cold mortality effects are expressed as the percentage change in daily mortality at 29°C (apparent temperature) and at –5°C relative to 15°C. Both 29°C and –5°C represent extremes that could plausibly result in physiologic stress and were reached on at least 80 days in the time series for every city analyzed. A number of papers have been published describing the shape of the dose response between temperature and mortality. Since the present goal was to examine effect modification, selecting two extreme temperatures at which to estimate the effects was an informative way of evaluating the research question.

Models were fit to each individual city to allow for city-specific variability in the association between weather, pollution, season, and mortality. Natural cubic splines for day of the week and barometric pressure were selected with degrees of freedom to minimize Akaike's Information Criterion (36). Degrees of freedom for the spline term for day of study (an integer value for day 1 to *n* of the time series) were selected to minimize the sum of autocorrelation in the residuals while also removing seasonal trends in the mortality data. Autoregressive terms (37) were added to the models for Chicago, Detroit, Pittsburgh, and Seattle to remove serial correlation remaining in the residuals. S-Plus 2000 (Mathsoft, Inc., Seattle, Washington) software was used to fit all of the models, and a more stringent convergence criterion than the one provided was used as the default (38).

For each city, separate robust Poisson regression models were fit to the daily death counts in each category of interest to examine effect modification (age, gender, race, educational level, and place of death). In addition, a combined effect estimate across all seven cities was calculated by using a random-effects model that weights the effect estimates by the inverse sum of within- and between-city variance, thus accounting for any heterogeneity among the cities in the summary effect estimates. Heat effects could be pooled for only five cities; in Seattle and Denver, the mean daily apparent temperature never exceeded 28°C.

In the second stage, we combined for each stratum the city-specific coefficients $\hat{\beta}$ by using the maximum likelihood method of Berkey et al. (39). We assumed that $\beta_i \sim N(\hat{\beta}, S_i + D)$, where $\hat{\beta}_i$ is the heat or cold coefficient in city *i*, $\hat{\beta}$ is the summary estimate from all of the cities, $\hat{S}_i$ is the estimated variance in city *i*, and *D* is the random variance component, reflecting heterogeneity in response among the cities.

RESULTS

Of the seven cities, Minneapolis had the lowest mean apparent temperature, –14.6°C, compared with Seattle, where the temperature never dipped below –8°C. The maximum daily mean apparent temperatures were about the same for all cities except Seattle and Denver, which did not exceed 28°C (table 1). The range in mean levels of particles across cities was not great, with a minimum of 28.1 μg/m^3 in Minneapolis and a maximum of 36.6 μg/m^3 in Detroit.

Chicago had the highest number of deaths, almost 300,000 over the 6 years, and Denver had the fewest, 36,717 from 1986 to 1993 (table 1). Detroit had the highest proportion of Blacks among the deceased, 40 percent, and Minneapolis the lowest, 4 percent. The distribution of deaths across gender and age was similar across the cities. The percentage of Denver, Minneapolis, and Seattle decedents who had more education was higher than that for the other cities. Detroit had the highest percentage of deaths outside a hospital (67 percent) and New Haven, Minneapolis, and Seattle the lowest, with the majority of deaths occurring in a hospital.

Combined effects for the seven cities at cold (–5°C) temperatures compared with 15°C temperatures, averaged over the previous 3 days, are presented in figure 1. With the exception of age and race, the confidence intervals for each pair of strata enclosed the point estimate of the others. The

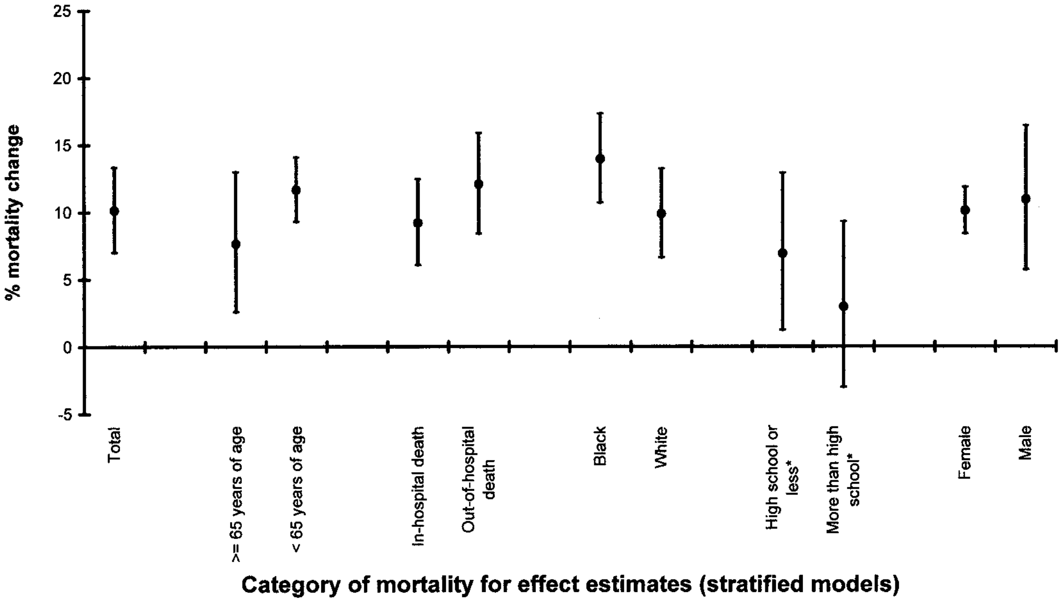

FIGURE 1. Combined estimates of excess mortality at –5°C (averaged over lags 1–3) compared with mortality at 15°C and 95% confidence intervals from a random-effects model for all US study cities except Seattle, Washington, and Denver, Colorado, 1986–1993 (1990–1993 for education strata). Model covariates include particulate matter less than 10 μm in aerodynamic diameter, barometric pressure, day of the week, day of study, and apparent temperature lag 0.

point estimates for those persons aged less than 65 years, Blacks, those with a high school education or less, and those dying outside a hospital were all approximately twice as high as those for their corresponding categories, whereas the point estimates for gender were approximately equal. All estimates controlled for the effects of PM_{10}, barometric pressure, day of the week, seasonal trends, and mean apparent temperature on the day of death.

Heat effects (percentage of excess deaths at 29°C relative to 15°C on the day of death) are shown in figure 2. Modification of the heat effect was stronger than for the cold effect for several of the factors considered. For three of the categories compared (race, place of death, and education), confidence intervals of the corresponding stratum did not enclose the point estimate of the other. In terms of magnitude, the effect estimates for out-of-hospital deaths and lower educational level were about eight and 10 times higher, respectively, than those for their reference categories. The effects for Blacks were more than twice those for Whites.

Confidence intervals for the age and gender categories both enclosed the other's point estimate. The heat effects shown in figure 2 controlled for PM_{10}, relative humidity, barometric pressure, day of the week, seasonal trends, and mean temperature averaged over the preceding 3 days.

City-specific and pooled results by each of the effect modifiers examined are presented in tables 2 (cold effects) and 3 (heat effects). With the exception of Detroit and Minneapolis, where effects were about equal, cold effects for Blacks were consistently higher than those for Whites. Out-of-hospital mortality associations were higher in most cities. For heat-related mortality, out-of-hospital effects were higher for every city, and race effects were consistent except for New Haven, where the mortality effects for Blacks and Whites were approximately equal.

In Chicago, respiratory-cause mortality was much more strongly associated with cold temperature than with hot (table 4), and a particularly strong effect modification was seen by age; compared with the elderly, young people experienced high respiratory-cause mortality for cold days. This finding was also the case for Blacks compared with Whites and for out-of-hospital deaths. Cardiovascular-cause mortality effects were approximately the same across corresponding age, place of death, and race strata for both heat and cold.

DISCUSSION

Study findings showed that the relation between hot temperature and mortality was modified by place of death, race, and educational level. Deaths occurring outside of a hospital, among those with a high school education or less, and among Blacks evidenced a much stronger temperature dependence than deaths inside a hospital, among those with more than a high school education, and among Whites, respectively. Evidence for effect modification of cold-related deaths by these same factors was weaker but in the same direction. Weak evidence for modification of the cold effect by age was observed, but temperature-related mortality effects were not differential by gender.

A number of previous studies have examined potential markers of vulnerability to temperature-related mortality and provide a context for interpreting our results. Heat-wave-related deaths in Chicago in 1995 occurred among people with medical problems who had no air conditioning and experienced social isolation (40). A study of the same

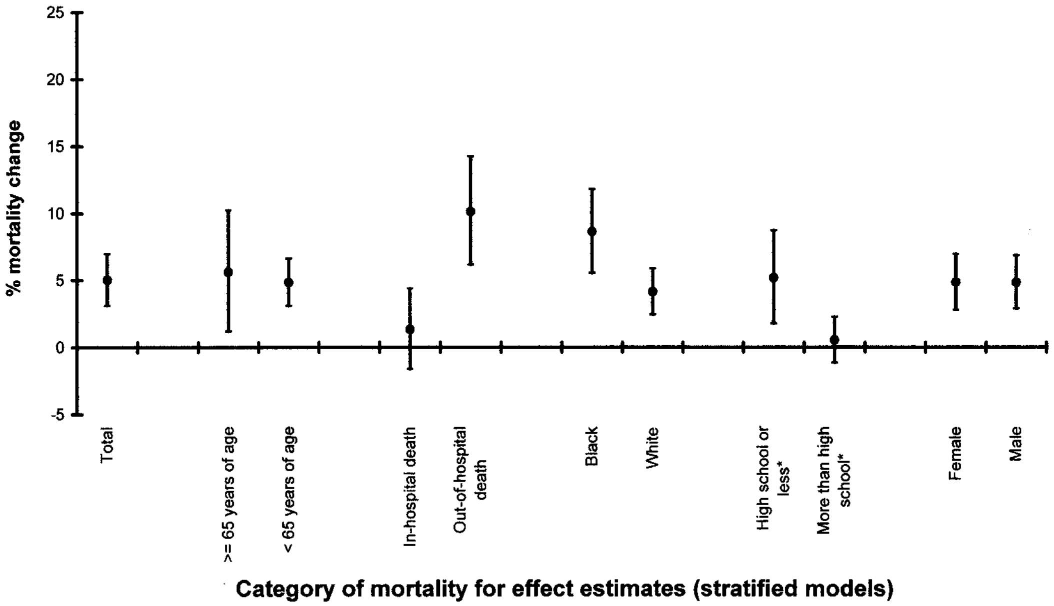

FIGURE 2. Combined estimates of excess mortality at 29°C (lag 0) compared with mortality at 15°C and 95% confidence intervals from a random-effects model for all seven US study cities, 1986–1993 (1990–1993 for education strata). Model covariates include particulate matter less than 10 µm in aerodynamic diameter, barometric pressure, day of the week, day of study, and apparent temperature average of lags 1, 2, and 3.

Chicago heat wave found that those deaths occurred disproportionately among the elderly (aged 65 years or older) and non-Hispanic Blacks (30). In Texas, heat-related death rates were higher among the elderly, men, Blacks, and persons involved in heavy labor (31). In the United Kingdom, winter mortality was not associated with a geographic indicator of

TABLE 2. Percentage change in daily mortality and 95% confidence intervals associated with a –5°C apparent temperature,* pooled and city-specific results (1988–1993 for Chicago; 1986–1993 for other US cities)†

	Pooled results		Chicago, Illinois		Denver, Colorado		Detroit, Michigan		Minneapolis, Minnesota‡		New Haven, Connecticut		Pittsburgh, Pennsylvania		Seattle, Washington	
	%	95% CI§	%	95% CI	%	95% CI	%	95% CI	%	95% CI	%	95% CI	%	95% CI	%	95% CI
Total mortality	10.1	7.0, 13.3	11.7	10.3, 13.1	3.1	–0.4, 6.7	12.8	10.9, 14.7	6.6	4.1, 9.2	16.2	12.6, 19.9	11.7	9.9, 13.6	8.6	4.4, 13.0
Gender																
Male	10.9	5.7, 16.4	13.6	11.7, 15.5	2.4	–2.3, 7.4	15.2	12.5, 17.9	2.6	–0.9, 6.3	23.6	18.1, 29.2	10.1	7.6, 12.7	10.0	4.2, 16.2
Female	10.1	8.4, 11.8	9.6	7.7, 11.5	5.5	0.5, 10.8	9.4	6.7, 12.1	10.4	6.9,14.1	10.1	5.4, 15.2	13.8	11.1, 16.4	8.2	2.2, 14.5
Race																
Black	14.0	10.7, 17.3	13.3	10.8, 15.9	10.5	–0.9, 23.2	12.3	9.4, 15.3	6.7	–6.3, 21.6	25.0	11.5, 40.2	15.4	9.9, 21.3	31.1	9.8, 56.6
White	9.9	6.6, 13.2	11.3	9.7, 12.9	2.8	–0.8, 6.5	14.3	11.9, 16.9	6.6	4.0, 9.3	15.2	11.4, 19.0	11.4	9.5, 13.4	7.0	2.6, 11.5
Educational level																
High school or less¶	6.9	1.2, 12.9	–2.7	–4.5, –0.9	3.9	–2.6, 10.8	8.5	5.4, 11.6	7.1	2.6, 11.7	15.8	8.8, 23.2	8.5	5.4, 11.7	9.0	–3.2, 22.7
More than high school¶	2.9	–3.0, 9.3	–1.8	–5.3, 1.8	–9.7	–17.2, –1.5	14.2	7.0, 21.8	–0.8	–7.0, 5.9	8.3	–4.1, 22.4	–1.2	–7.1, 5.1	0.3	–14.1, 17.1
Age (years)																
≥65	7.6	2.6, 13.0	11.4	9.7, 13.1	7.7	2.8, 9.7	15.0	12.6, 17.5	9.3	6.3,12.5	13.9	9.6, 18.3	14.6	12.5, 16.8	6.9	1.9, 13.9
<65	11.7	9.3, 14.1	13.0	10.6, 15.4	2.1	–5.0, 9.8	7.1	4.1, 10.3	–2.2	–6.9, 2.8	19.1	11.5, 27.3	4.7	1.1, 8.4	11.6	3.7, 20.1
Place of death																
Out of hospital	12.1	8.4, 15.9	14.5	12.3, 16.7	3.7	–2.0, 9.7	18.3	14.9, 21.8	8.1	4.7, 11.7	14.7	9.7, 19.9	14.8	11.9, 17.9	8.2	2.7, 13.9
In hospital	9.2	6.1, 12.4	9.5	7.8, 11.2	6.2	0.7, 12.0	10.2	8.0, 12.5	2.8	–0.9, 6.6	18.0	11.8, 24.5	10.0	7.7, 12.4	8.9	2.6, 15.6

* Defined as a person's perceived air temperature.

† Estimates are relative to a 15°C apparent temperature and control for barometric pressure, particulate matter less than 10 µm in aerodynamic diameter, time trend, day of the week, and apparent temperature lag 0 (cold effect was derived from apparent temperature averaged for lags 1, 2, and 3).

‡ Also includes St. Paul.

§ CI, confidence interval.

¶ Education was not recorded before 1990, so the data are from 1990–1993 for all US seven cities.

TABLE 3. Percentage change in daily mortality and 95% confidence intervals associated with a 29°C apparent temperature,* pooled and city-specific results (1988–1993 for Chicago; 1986–1993 for other US cities)†

	Pooled results		Chicago, Illinois		Detroit, Michigan		Minneapolis, Minnesota‡		New Haven, Connecticut		Pittsburgh, Pennsylvania	
	%	95% CI§	%	95% CI	%	95% CI	%	95% CI	%	95% CI	%	95% CI
Total mortality	5.0	3.1, 7.0	4.5	2.3, 6.7	7.5	4.2, 10.8	2.4	–2.1, 7.1	7.7	2.9, 12.8	3.1	–0.5, 6.9
Gender												
Male	4.8	2.9, 6.8	4.7	1.9, 7.7	1.2	–11.6, 15.8	0.8	–5.5, 7.5	7.8	1.0, 15.0	2.6	–2.4, 7.8
Female	4.8	2.8, 6.9	4.1	1.0, 7.2	6.8	2.1, 11.8	5.0	–1.3, 11.7	6.2	–0.5, 13.2	3.8	–1.3, 9.1
Race												
Black	8.6	5.6, 11.8	5.9	2.0, 9.9	12.0	6.8, 17.4	17.0	–7.8, 48.4	6.8	–9.3, 25.7	12.5	1.4, 24.8
White	4.1	2.4, 5.9	4.1	1.5, 6.7	5.5	1.4, 9.7	2.3	–2.4, 7.1	7.9	2.8, 13.2	2.0	–1.7, 6.0
Educational level												
High school or less¶	5.2	1.8, 8.7	1.1	0.2, 2.0	8.1	2.4, 14.2	9.2	0.6, 18.5	8.1	–1.3, 18.4	7.6	1.1, 14.5
More than high school¶	0.5	–1.2, 2.2	0.8	–1.0, 2.6	–4.6	–15.6, 7.9	–7.9	–18.8, 4.4	9.6	–8.1, 30.7	–2.7	–14.9, 11.2
Age (years)												
≥65	5.6	1.2, 10.2	4.2	1.6, 6.9	5.4	1.4, 9.5	2.5	–2.7, 8.1	8.7	2.9, 14.9	5.3	1.1, 9.6
<65	4.8	3.1, 6.6	5.3	1.8, 9.0	12.3	6.7, 18.1	–0.5	–9.1, 9.0	7.8	–1.9, 18.4	0.5	–6.6, 8.2
Place of death												
Out of hospital	10.1	6.2, 14.2	7.3	3.9, 10.8	17.5	11.6, 23.8	5.6	–0.5, 12.1	9.1	2.4, 16.4	11.8	5.7, 18.2
In hospital	1.3	–1.6, 4.4	2.6	–0.1, 5.3	3.4	–0.4, 7.3	–3.8	–10.1, 3.0	5.9	–2.1, 14.5	–2.0	–6.3, 2.6

* Defined as a person's perceived air temperature.

† Estimates are relative to a 15°C apparent temperature and control for barometric pressure, particulate matter less than 10 μm in aerodynamic diameter, time trend, day of the week, and apparent temperature averaged over lags 1, 2, and 3 (heat effect is expressed for apparent temperature lag 0).

‡ Also includes St. Paul.

§ CI, confidence interval.

¶ Education was not recorded before 1990, so the data are from 1990–1993 for all five US cities.

social deprivation based on a composite of census variables (41); census-based measures of deprivation and excess wintertime mortality, except for lack of central heating (42); or socioeconomic deprivation, measured at the individual level, although being elderly and having ischemic heart disease were (32). Excess morbidity occurred among the

TABLE 4. Percentage change in daily mortality and 95% confidence intervals associated with a –5°C (average of lags 1, 2, and 3) and a 29°C (lag 0) apparent temperature* for Chicago, 1988–1993, by cause of death, age, place of death, and race†

	Cardiovascular-cause mortality				Respiratory-cause mortality			
	Cold (–5°C)		Hot (29°C)		Cold (–5°C)		Hot (29°C)	
	%	95% CI‡	%	95% CI	%	95% CI	%	95% CI
Total	10.0	7.6, 12.3	0.86	–2.7, 4.6	19.1	13.5, 25.1	–1.9	–9.9, 6.9
Age (years)								
<65	11.9	6.9, 17.1	–0.1	–7.4, 7.8	39.9	25.7, 55.7	2.2	–15.1, 23.0
≥65	9.7	7.0, 12.4	1.63	–2.5, 5.9	14.3	8.3, 20.6	–2.5	–11.2, 7.1
Place of death								
In hospital	10.7	7.5, 13.9	–0.51	–5.3, 4.5	12.7	6.5, 19.1	–3.5	–12.5, 6.3
Out of hospital	9.7	6.3, 13.2	3.1	–2.2, 8.7	44.3	31.6, 58.3	6.4	–9.6, 25.3
Race								
Black	14.9	9.9, 20.1	–0.95	–8.0, 6.6	32.4	20.9, 44.9	–3.6	–17.7, 12.8
White	9.0	6.3, 11.7	1.71	–2.5, 6.1	14.2	7.9, 21.0	0.0	–9.6, 10.5

* Defined as a person's perceived air temperature.

† Estimates are relative to a 15°C apparent temperature and control for barometric pressure, particulate matter less than 10 μm in aerodynamic diameter, time trend, day of the week, and other temperature term (lag 0 for heat; lags 1, 2, and 3 for cold).

‡ CI, confidence interval.

affluent in the winter and among the less affluent in the summer (43). A study of eight European regions with diverse climates found cold-related mortality to be most pronounced among people who lived in cooler homes, were more lightly clothed, and were less active outdoors (44).

An analysis of the temperature and mortality relation in 11 US cities examined several census-based socioeconomic indicators, including percentage of persons older than age 65 years, older than age 65 years and disabled, and older than age 25 years with no high school degree; percentage of persons living in poverty; and percentage of occupied homes with heating and air conditioning (22). These researchers found that the shape of the association differed little by age, but they observed the smallest effect among those less than age 65 years and the largest effect among those more than age 75 years (22). The cold-related mortality association was stronger among those more than age 65 years and was weaker when a higher fraction of the homes had heating (22). Heat-related mortality associations were higher in areas with higher percentages of people without high school diplomas, living in poverty, and living in homes with air conditioning (22).

In contrast to the previous study, the present analysis used individual-level data on socioeconomic indicators, including educational attainment and race, enabling inferences to be drawn about the individual, not just the contextual effects, of these variables. Although limitations of using racial classifications in epidemiologic research have been discussed (45), race is one of the few indicators available from death certificates that reflects differential distributions for a variety of socioeconomic conditions and health outcomes in the United States and can even be thought of as a contextual variable, rather than an individual characteristic, for just this reason (46). Being Black can be associated with a variety of socially disadvantageous circumstances in the United States; for example, Blacks are more likely than Whites to live in impoverished neighborhoods, even if they have similar incomes (47). Although overall temperature-related mortality was higher among Blacks, the city-specific estimates for race were somewhat heterogeneous. All cities but New Haven showed higher heat effects among Blacks. The point estimates for cold effects among Blacks were higher than for Whites for all cities except Detroit. The pooled results are consistent with previous studies showing a higher risk of heat-related mortality among Blacks (31) and according to other factors, including geographic measures of percentage living in poverty and percentage with a high school diploma, that vary by race (22).

Educational attainment can be a robust indicator of socioeconomic position, predicting income, living conditions, and occupation (48), and those persons with more years of attained education generally have greater wealth and an improved quality of life (49). Higher mortality rates overall have been observed among the less-educated in US-based cohorts (50). For cold effects, all cities but Detroit and Chicago showed higher effects among the less educated. For the heat effect, the point estimates for the less educated were higher for all cities except New Haven. Our results are consistent with Curriero et al.'s (22) study of the contextual effect of living in an area in which a higher proportion of the people lack high school diplomas.

Place of death was the strongest effect modifier, and the difference was particularly noteworthy for heat effects. The direction of the effect modification by place of death was consistent across all individual-city estimates for heat. The same homogeneity for city-specific associations was observed for the cold effect, except in Denver and Seattle, although the confidence intervals for both of these cities enclosed the other stratum's point estimates. The consistency of this observation across the cities lends support to the biologic plausibility that exposure to ambient conditions, more likely among those who are not hospitalized, can contribute to mortality.

The cause-specific analysis for Chicago showed that cold-associated respiratory mortality more strongly affected Blacks, those who died outside of a hospital, and the young. Chicago is by far the largest city with the greatest influence on the pooled estimates, hence the strong effects among the young here helped explain the effect modification by age in the pooled analysis, which contradicts previous studies. The finding that the relative effect of cold weather in Blacks compared with Whites was greater than for all-cause mortality suggests that further research on cause-specific deaths is warranted.

Unlike in other recent multicity analyses of temperature and mortality associations (15, 22), we controlled for the effects of PM_{10} in the models. The level of confounding if particulate pollution is not included can be substantial. The amount of confounding by PM_{10} differed from city to city; in some cases, the direction of the effect was reversed, but, in other cases, no significant differences were found in the crude and adjusted temperature effects. In light of the known and consistent associations between PM_{10} and mortality, however, control for this pollutant is an important strength of the present study.

The factors contributing to the heterogeneity in effect modification by race and education across cities deserve further exploration. Our study was limited by classifying people across an entire metropolitan area by characteristics including race and education. A sociologic analysis of heat-related mortality in Chicago showed that features of neighborhoods on a relatively small geographic scale (e.g., amount of pedestrian traffic, small shops, public meeting places) affect survival rates, even when investigators controlled for resident demographics (similar age and income distribution) (51). Although our results suggest that socioeconomic disadvantage results in more vulnerability to temperature-related mortality, further studies using a combination of individual- and neighborhood-level indicators, preferably at finer geographic resolution, may be required. In addition, evaluations of causes of death such as heat stroke or hypothermia may be necessary to more specifically target populations and identify public services and infrastructure necessary to prevent deaths on extreme-temperature days.

A further enhancement for future research would be consideration of alternative composite indices of meteorologic parameters that affect human comfort and health. Although we did use the index of apparent temperature and accounted for barometric pressure in the models, other approaches, such as the physiologic equivalent temperature (52), make use of information on other weather conditions including wind, cloud cover, and solar radiation and might enable a more apt characterization of human exposure to extreme weather conditions.

Our results suggest that the effects of temperature extremes on mortality fall disproportionately on those persons at relative social disadvantage in the United States. International collaborative studies on climate change have addressed equity concerns across nations (noting, for example, that island nations would be much more affected by sea-level rise and that many developing countries will experience worse consequences than industrialized nations that emit higher quantities of greenhouse gases). Our work adds further evidence to support the claim of the Intergovernmental Panel on Climate Change that "the impacts of climate change will fall disproportionately upon developing countries and *the poor persons within all countries* [emphasis added]" (53, p. 77).

The present study provides new information on factors that may affect sensitivity to temperature-related mortality. The fact that effect modification by place of death and by race (for the heat effect) was similar across all of the cities enhances the likelihood that these factors are valid markers of increased susceptibility. In the broader context of efforts to understand how the world climate affects human health, our results further support the plausibility of direct effects of temperature on human health, especially in light of the place-of-death finding. They also suggest that socioeconomic position, in this case as indicated by Black race and lower educational attainment, confers additional vulnerability to the effects of extreme temperature.

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