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# Temperature and Mortality in Nine US Cities

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## Abstract

**Background—**Extreme temperatures have been associated with increased mortality worldwide. The extent to which air pollutants may confound or modify this association remains unclear.

**Methods—**We examined the association between mean apparent temperature and total mortality in 9 cities across the United States during the warm season (May to September) from 1999 to 2002. We applied case-crossover and time-series analyses, adjusting for day of the week and season in time-series analysis. City-specific estimates were then combined using a meta-analysis. A total of 213,438 deaths for all causes occurred in these cities during the study period.

**Results—**We found that mortality increased with apparent temperature. A 5.5°C (10°F) increase in apparent temperature was associated with an increase in mortality of 1.8% (95% confidence interval = 1.09% to 2.5%) when using case-crossover analysis and with an increase of 2.7% (2.0% to 3.5%) using the time-series analysis.

**Conclusions—**This study provides evidence of increased mortality due to elevated apparent temperature exposure, with no confounding or effect modification due to air pollution.

Greenhouse gas emissions from human activity are projected to increase overall average temperatures, as well as the frequency of extreme weather events such as heat waves, across the world.[1-5] These changes will have potentially serious implication for human health, and the evaluations of the links between climate change and health in terms of describing and quantifying the impact of these changes, can help identify vulnerable populations and aid policy makers in formulating preventive actions.[6-9] In colder climate, the increase of global temperature may benefit health,[10] although studies have suggested that the wintertime increase in mortality is due to infectious disease, and not direct effects of cold weather.[11] Because climate change will likely increase the average temperature, our study focused on the effects of weather in the warm season.

The effect of temperature extremes in association with increased mortality are well studied[12-21]; greater susceptibility has been reported for the elderly and for those with a lower socioeconomic status.[14,17,20,22,23] The underlying mechanisms for the increase in mortality may be related to the stress placed on the respiratory and circulatory systems to increase heat loss through skin surface blood circulation.[12,24] This stress coupled with an increase in blood viscosity and cholesterol levels with high temperatures[25] may increase the risk for cardio-respiratory deaths.

What is less clear is the extent to which these previously reported associations are confounded by air pollution. O'Neill et al[26] examined this issue in 2 Mexican cities, and

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NIH-PA Author Manuscript
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reported a moderate degree of confounding by air pollution, but this issue and the parallel issue of effect modification have not been thoroughly explored. Moreover, examination of effect modification has generally used simple multiplicative interaction terms, whereas with thin plate splines, it is possible to examine more complex types of interactions.

Our hypothesis is that increases in apparent temperature are associated with increases in total mortality, and that the effect is independent of air pollution.

We examined the association between temperature and mortality in 9 US cities with a range of climatic and pollution patterns. We focused on apparent temperature and on the summer season, and examined confounding and modification of risk by air pollutants using both time-series and case-crossover analyses.

## METHODS

### Data

**Mortality Data—**We selected 9 US cities outside of California that had sufficient mortality and daily air pollution data and were representative of both cold and warm climates: Birmingham, Alabama; Boston, Massachusetts; Chicago, Illinois; Detroit, Michigan; Dallas, Houston, Texas; Minneapolis/St. Paul, Minnesota; Philadelphia, Pennsylvania; and Phoenix, Arizona.

These cities represent a range of summer temperatures (with the average apparent temperature ranging from 20°C to 32°C) and a range of particulate air matter with aerodynamic diameter less than 2.5 mm ($PM_{2.5}$) coexposures (with an average across all cities ranging from 8 to 26 $\mu g/m^3$).

Analyses were conducted on the city level, which in most cases was restricted to a single county. However, we used multiple counties for Minneapolis-St. Paul (Ramsey and Hennepin), and Boston (Middlesex, Norfolk, Suffolk), where the city's population extends beyond the boundaries of 1 county.

Individual mortality data were obtained from the National Center for Health Statistics (NCHS) for the years 1999 and 2000, and for the years 2001 and 2002 from the state public health departments of Massachusetts, Michigan, Minnesota, Texas, and Pennsylvania. The mortality files provided information on the exact date of death and the underlying cause of death.

For this study we selected all-cause daily mortality excluding any deaths from accidental causes (ICD-code 10th revision: V01-Y98, ICD-code 9th revision: 1-799).

**Environmental Data—**We obtained $PM_{2.5}$ and ozone data from the US Environmental Protection Agency's Air Quality System Technology Transfer Network for the same years of the mortality data. In most cities particulate air matter with aerodynamic diameter less than 2.5 mm ($PM_{2.5}$) monitoring started in 1999. For the Boston area we used daily $PM_{2.5}$ concentration extracted from the Harvard School of Public Health monitor located in downtown Boston, as there data were more complete. For ozone we used 8-hour daily mean concentrations during the hours of 8 AM to 5 PM.

When multiple monitors were present in a city we estimated an average daily value for the city. Since all monitors do not report on each day, simple means could vary based on which monitor is missing, rather than true variation from day to day. To avoid this, we used an algorithm previously described[27,28] that averages the monitors while accounting for the

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different monitor-specific means and variances. However, before applying this algorithm, we obtained multiple correlation coefficients for each monitor (correlated with all other monitors in the city). Those monitors falling in the low 10th percentile of the distribution of the median values, across all cities, were excluded from the analyses. If no monitor reported on a given day, the pollution value was missing.

We obtained local meteorological data such as mean, maximum, minimum temperature, and dew point temperature, from the United States Surface Airways and Airways Solar Radiation hourly data.[29] In this study we used apparent temperature, which is a composite index of human discomfort due to combined heat and high humidity; this index should characterize the physiologic experience better than temperature alone because it takes into account the effect of humidity on the body. It was developed by Steadman[30] and is based on physiological studies of evaporative skin cooling for various combinations of ambient temperature and humidity. When the dew-point temperature is 57.2°F (14°C), the apparent temperature equals the actual air temperature. At higher dew-points, the apparent temperature exceeds the actual temperature and measures the increased physiologic heat stress and discomfort associated with higher than comfortable humidity. When the dew-point is less than 57.2°F the apparent temperature is less than the actual air temperature and measures the reduced stress and increased comfort associated with lower humidity and greater evaporative skin cooling. Apparent temperatures greater than 80°F are generally associated with some discomfort. Values approaching or exceeding 105°F are considered life-threatening, with severe heat exhaustion or heatstroke possible if exposure is prolonged or physical activity high. Apparent temperature (AT) is defined as an individual's perceived air temperature given the humidity. Apparent temperature was calculated with the following formula[30,31]:

$$AT = -2.653 + (0.994 \times Ta) + \left(0.0153 \times Td^2\right)$$

where Ta is air temperature and Td is dew point temperature.

Apparent temperature has been used in previous studies[26,32] to examine extreme temperature effects; while in this study we present the effect of the more typical temperature exposure that is commonly experienced during summer; however, we performed sensitivity analyses using alternative definitions (mean temperature, maximum temperature) to ensure our results were robust to the exposure definition.

**Statistical Methods—**To investigate the association between weather and mortality we used both time-series and case-crossover analyses.

The case-crossover design was developed as a variant of the case-control design to study the effects of transient exposures on acute events.[33] This design compares each subject's exposure experience in a time period just prior to a case-defining event with that subject's exposure at other times. Since there is perfect matching on all measured or unmeasured subject characteristics that do not vary over time, there can be no confounding by those characteristics. If in addition, the control days are chosen to be close to the event day, subject characteristics that vary slowly over time are also controlled by matching.

Bateson and Schwartz[34,35] demonstrated that by choosing control days close to event days, even very strong confounding of exposure by seasonal patterns could be controlled by design in the case-control approach. Levy and Lumley[36] showed that a time-stratified approach to choosing controls resulted in a proper conditional logistic likelihood, and Schwartz and coauthors[37] demonstrated with simulation studies that this approach gave

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unbiased effect sizes and coverage probabilities even with strong seasonal confounding. We used this same stratified approach in our analysis. We defined the hazard period as the day of death; we chose as control days every third day in the same month and year as the case.

The data were analyzed using conditional logistic regression analysis (PROC PHREG in SAS, SAS software release 8.2. 2001, SAS Institute, Cary, NC).

The time series of daily counts of mortality and daily weather were investigated with a generalized additive model, with a quasi-Poisson link function to account for overdispersion. In the model we controlled for season using natural splines with 4 degrees of freedom per year and subsetting for summer months, and day of the week with indicator variables.

These models were fit in R (The Comprehensive R Archive Network: http://cran.r-roject.org/).

## Data Analysis

**Exploratory Analysis—**We first conducted exploratory analyses to determine whether the use of linear temperature terms for the warm seasons was appropriate. This was accomplished by fitting time series models for the full year in each city, using natural splines for apparent temperature with 4 degrees of freedom. These models used 4 degrees of freedom per year to control for season. If the exploratory plots from those models looked roughly linear for warm temperatures, the remaining models, restricted to the warm season, were created using linear temperature terms, which facilitate the reporting of odds ratios.

**Main Analysis—**The analysis was first conducted in each city separately; we used individual deaths in the case-crossover study and aggregated counts of daily deaths for the time-series analysis. In each model we controlled for day of the week with indicator variables. For time-series analyses we also controlled for long term time trends using natural splines with 4 degrees of freedom per year for time trend, and subsetting on the May to September period.

We investigated the association between weather and mortality during the summer period (May to September) using a linear term for apparent temperature on the same day in the model. We examined confounding and effect modification by each pollutant. We added each pollutant separately in the model to see if they confounded the association between apparent temperature and mortality.

We analyzed effect modification and nonlinearity in the association with temperature by including in the model a bivariate thin plate regression spline of apparent temperature and pollution and then investigated possible interactions by looking at the 3-dimensional plots. If any plot was suggestive we considered multiplicative interaction terms between the temperature and the pollutant. We considered an interaction to be significant if the multiplicative interaction term was statistically significant or if a thin plate spline with more than 2 degrees of freedom was significant in a likelihood ratio test, compared with a model with linear terms for pollution and temperature. The degrees of freedom for the thin plate spline were chosen using cross-validation.

**Sensitivity Analyses—**We applied several sensitivity analyses. First, we considered the possibility that moving averages over a period longer than 1 day are better predictors of the temperature-mortality association. We compared the effect of the same-day temperature exposure (lag 0) to moving averages of the same day and previous 3 days (lag 03), or the previous 3 days (lag 13). We then looked at other temperature definitions, replacing apparent temperature with the combination of either mean, minimum, and maximum

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temperature with dew point temperature. We used adjusted deviance to choose the best fitting among these models. We also analyzed only days with apparent temperature greater than 23.8°C (75°F). Finally we considered a regional analysis.

If a linear term is used for pollution, to control for confounding, several aspects of confounding could be missed. If the association with the confounder is nonlinear, or if it varies over time, there may be residual confounding. To protect against these risks, we used an alternative approach of matching control days to the same concentrations of air pollutants as case days.[23]

**Combined Results—**In a second stage of the analysis, the city-specific results were combined using the multivariate meta-regression technique of Berkey and coworkers.[38] To be conservative we report the results incorporating a random effect, regardless of whether there was significant heterogeneity.

We report the results as percent increases in mortality for an increase in apparent temperature of 5.5°C, which correspond to 10°F. We provide 95% confidence intervals (CIs) for these results.

## RESULTS

In each city we first plotted the smoothing function of apparent temperature over all year to look at possible nonlinearity (Fig. 1). From the plots it is clear that starting from an apparent temperature of 10°C or 15°C, depending on the city, the association between mortality and apparent temperature become linear. This is the temperature range where our summertime analysis focuses.

In the sensitivity analyses, we found that lag 0 apparent temperature had the best model fit compared with the moving averages of multiple days. We therefore report here the results analyzing the effect of apparent temperature only during warmer months (May to September) and used a linear term for apparent temperature at lag 0.

Tables 1 and 2 present the city-specific descriptive statistics for the months May to September. The total population in the study consisted of 213,438 deaths for all causes. We had 3 cities with 2 years of data, and the mean daily deaths in the 9 cities ranges between 21.3 and 110.3.

Table 2 shows the city-specific descriptive statistics for apparent temperature and the pollutants; apparent temperature means for the 9 counties ranged from 20.1°C to 31.6°C, the 8 hour daily mean ozone concentrations ranged from 39.2 to 57.5 ppb, and $PM_{2.5}$ from 8.2 to 23.3 $\mu g/m^3$.

Figure 2 shows the results for each county followed by the meta-analyses estimates for all 9 counties. We found that mortality increased with apparent temperature. A 5.5°C (10°F) increase in apparent temperature was associated with an increase in mortality of 1.8% (95% CI = 1.09% to 2.5%) when using case-crossover analysis and with an increase of 2.7% (2.0% to 3.5%) from the time-series analysis.

Table 3 present the results for all-cause mortality, using both methods, for apparent temperature alone and with evaluation of confounding by each air pollutant. The results did not change when adjusting for $PM_{2.5}$, while the effect decreased when adjusting for ozone. In the table we also present the results of a case-crossover analysis where we matched by ozone, to reduce the possibility of residual confounding that may have resulted from simply adding each pollutant to the model. Because the number of days with the same ozone

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concentration is very low, to include more control days we chose controls by matching with concentrations rounded by 2 ppb of ozone. This result produced a similar estimate effect (1.8% [95% CI =−0.3 to 4.0]) as in the original analysis.

When we included the bivariate thin plate spline between apparent temperature and air pollution in the model to examine possible interactions, the Generalized Cross-validation Criterion always chose 2 degree of freedom for the spline in each city, indicating that no significant interactions were present. Figure 3 shows the 3-dimensional plot of the bivariate thin plate spline between apparent temperature and ozone estimated with 2 degrees of freedom for the city of Boston.

Similarly, in a parametric model with an interaction term between apparent temperature and each pollutant no significant interactions were found.

The results of the sensitivity analyses, looking at the effect of mean, maximum, and minimum temperature, produced similar estimates, even if the results for mean temperature were higher using both methods (Table 4).

In regional analyses, we found that the 3 southern cities (excluding Phoenix) had a significantly lower risk (0.2% increase [95% CI =−1.1 to 1.5]) compared with the results of the other 5 colder cities combined (2.3% increase [95% CI = 1.7 to 2.9]). These results were from the case-crossover analysis, although the time-series study produced similar findings.

## DISCUSSION

We found an effect of apparent temperature on mortality from nonaccidental causes in summer months, when the dose-response relationship between mortality and temperature was shown to be linear. The same results were obtained when using other representations of temperature, even though the effect was higher when using mean temperature; the risk was not much increased when we examined days with temperature higher than 75°F instead of looking at summer months. Importantly, we found no effect modification by either particles or ozone and no confounding by particles, although we did find a moderate degree of confounding by ozone.

When comparing the results by type of methodology, the use of time-series analysis showed higher risks than did the case-crossover analysis, but this was not true in each county. The reason for this could be a better control for season in case-crossover analysis; long-term seasonal trends are an important potential confounder in the study of mortality and temperature; in a previous time-series study,[26] halving the number of degree of freedom for the seasonal spline induced confounding. Other studies that analyzed the mortality-temperature relationship comparing case-crossover and time-series analysis found similar results with the 2 methods.[23,39]

An important feature of this analysis was the inclusion of the pollutants to examine confounding and effect modification. An analysis[40] done with similar methods but carried out in 9 counties in California, found a 2% to 3% increase in all-cause mortality per 10°F increase in apparent temperature, showing results comparable to ours; no effect modification or confounding due to air pollution was found in the study. O'Neill and coauthors[26] found a small decrease in the association between temperature and mortality when adding ozone and $PM_{10}$ singly or jointly. Similarly to our analysis, Ren and coauthors[41] fit a bivariate surface model to examine effect modification due to $PM_{10}$ in Brisbane, Australia, and found that $PM_{10}$ significantly modified the effects of temperature on respiratory and cardiovascular hospital admissions, all nonexternal-cause mortality, and cardiovascular mortality at different lags. The same authors in another study[42] found that ozone positively modified the

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association between temperature and cardiovascular mortality, with stronger temperature-cardiovascular mortality associations when the ozone concentration where higher.

We did not find confounding by fine particulates, while we observed a lower effect when adjusting for ozone. The result of the case-crossover analysis matching by ozone instead did not show a decrease in the temperature effect; again this could be explained by a better control of seasonality with the case-crossover analysis, because matching by ozone in the same year and month results in controlling not only for season but also for the interaction between season and ozone. Differences between our study and others in terms of effect modification by any of the pollutants could be due to several reasons such as different type of modeling and methodology, different outcomes, and different temperature/pollution effect in different regions.

We also found a smaller risk in the warmer southern cities (excluding Phoenix) compared with the colder cities. This result was previously found[14,18,43] and could be explained by the fact that persons in warmer climates tend to be more acclimatized to warm weather and tend to be more vulnerable to cold weather, while heat-related deaths occur more in cities where extreme heat is rare; adaptation to the local climate might occur by physiologic acclimatization, behavioral patterns, or other adaptive mechanisms.[44]

One limitation of this study is that we could not examine socioeconomic variables and personal characteristics (such as race, age, income level, or air conditioning use) which have previously been shown to modify the association.[14,17,20,22,23] We focus on total mortality and did not examine specific causes of mortality that might identify susceptible population.

In conclusion, our study provides evidence of increased mortality due to mean temperature exposure during times other than heat wave, even when adjusting by air pollution; we also found evidence of acclimatization. Even though further increases in high temperatures due to climate change might be mitigated by adaptive mechanisms, the adverse impact of heat is expected to outweigh these benefits.

## Acknowledgments

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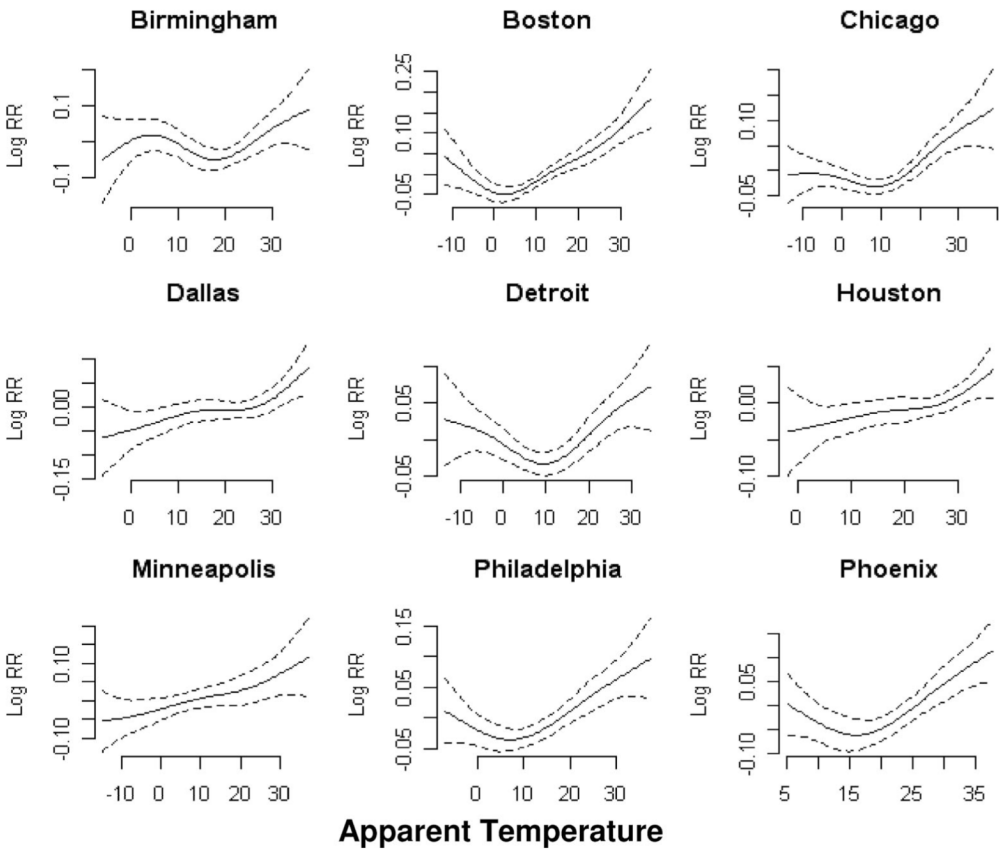


**FIGURE 1.**
City-specific plots of the smoothing function (solid line) of apparent temperature over all year, with 95% CIs (dashed line).

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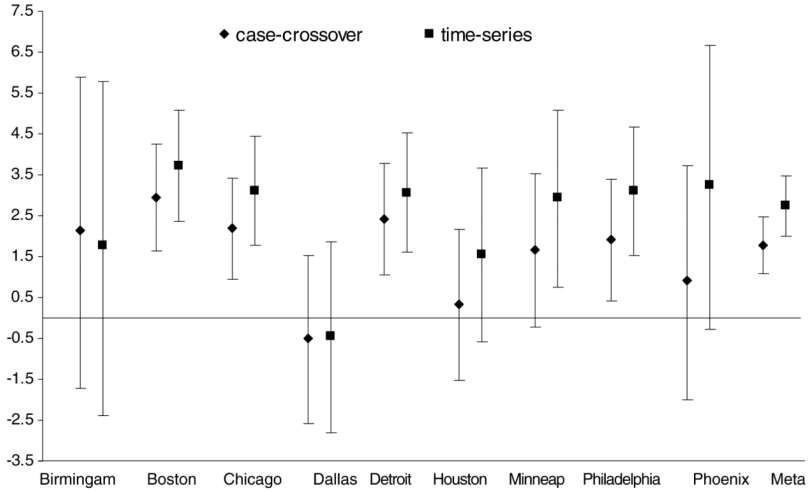


**FIGURE 2.**

Percent increase (and 95% CI) in nonaccidental mortality for an increase in mean apparent temperature of 5.5°C (10°F) in 9 US cities; city-specific and meta-analysis results using case-crossover and time-series analysis.

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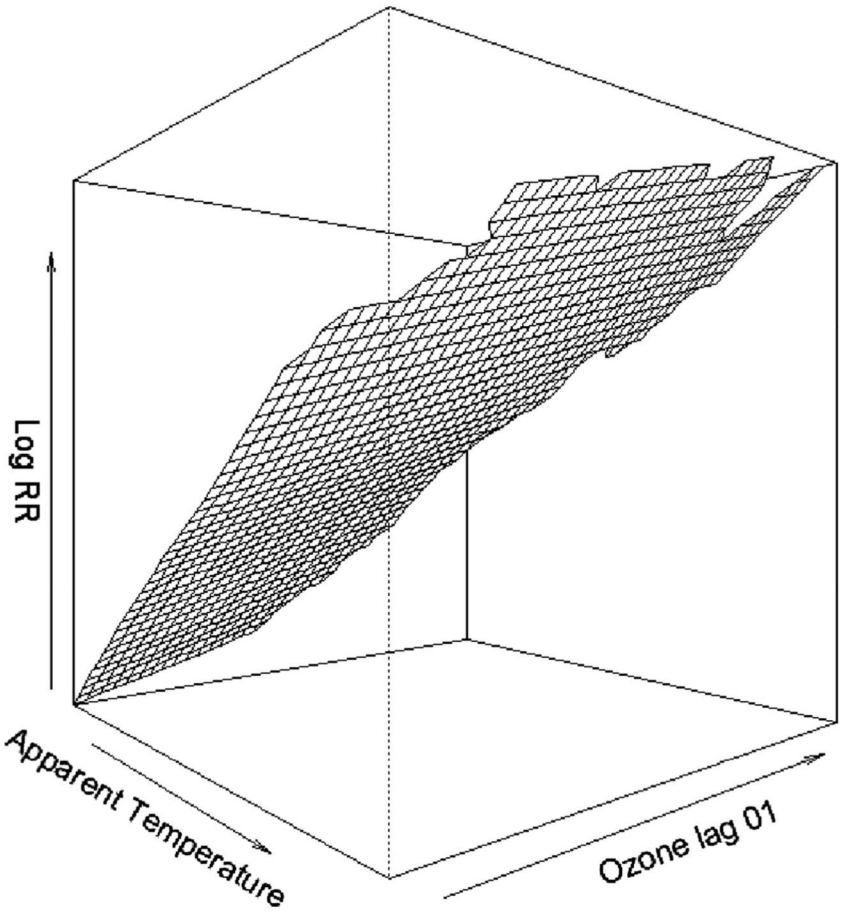


**FIGURE 3.**
For Boston, MA: 3-dimensional plot of the bivariate thin plate spline between apparent temperature and ozone lag 01, with 2 degrees of freedom.

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**TABLE 1**

Descriptive Statistics by County, May to September 1999–2002

| City, State | Years of Study | 2000 Population[a] | Total Deaths From All Causes | Mean Daily All-Cause Deaths | Days With Apparent-Temperature Data | Days With $PM_{2.5}$ Data | Days With Ozone Data |
|---|---|---|---|---|---|---|---|
| Birmingham, AL | 1999–2000 | 662 | 6775 | 22.1 | 306 | 306 | 306 |
| Boston, MA | 1999–2002 | 2806 | 33111 | 54.1 | 610 | 605 | 612 |
| Chicago, IL | 1999–2000 | 5377 | 33752 | 110.3 | 306 | 194 | 306 |
| Dallas, TX | 1999–2002 | 2219 | 21830 | 35.7 | 612 | 557 | 612 |
| Detroit, MI | 1999–2002 | 2061 | 28401 | 46.4 | 612 | 591 | 612 |
| Houston, TX | 1999–2002 | 3401 | 34118 | 55.7 | 612 | 490 | 612 |
| Minneapolis/St. Paul, MN | 1999–2002 | 1627 | 13028 | 21.3 | 612 | 507 | 0 |
| Philadelphia, PA | 1999–2002 | 1518 | 25822 | 42.2 | 612 | 562 | 612 |
| Phoenix, AZ | 1999–2000 | 3072 | 16601 | 54.3 | 306 | 304 | 306 |

[a]In thousands.

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**TABLE 2**

Mean and 25th and 75th Quartiles for Temperature and Pollutants by County, May to September 1999–2003

| | $PM_{2.5}$ (μg/m$^3$) | | | Ozone Mean 8 h (ppb) | | | Apparent Temperature (°C) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **25%** | **75%** | **Mean** | **25%** | **75%** | **Mean** | **25%** | **75%** |
| Birmingham | 23.3 | 16.3 | 29.4 | 55.5 | 41.4 | 68.0 | 27.7 | 24.7 | 31.0 |
| Boston | 11.7 | 6.0 | 15.0 | 42.1 | 30.1 | 51.2 | 20.1 | 15.9 | 24.4 |
| Chicago | 16.2 | 9.4 | 20.6 | 39.2 | 29.1 | 47.6 | 21.0 | 16.3 | 25.7 |
| Dallas | 14.1 | 9.2 | 17.4 | 50.6 | 35.9 | 64.1 | 30.1 | 27.6 | 33.9 |
| Detroit | 16.5 | 9.1 | 21.5 | 44.0 | 31.8 | 54.4 | 20.7 | 15.9 | 25.7 |
| Houston | 13.3 | 9.2 | 16.1 | 44.5 | 27.5 | 58.8 | 31.2 | 29.7 | 34.0 |
| Minneapolis | 10.0 | 6.1 | 12.2 | — | — | — | 20.0 | 14.9 | 25.2 |
| Philadelphia | 16.0 | 8.9 | 20.7 | 45.2 | 33.0 | 56.7 | 23.6 | 19.2 | 28.2 |
| Phoenix | 8.2 | 6.7 | 9.4 | 57.5 | 49.6 | 64.6 | 31.6 | 29.0 | 35.2 |

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## TABLE 3

Meta-Analysis Results for Apparent Temperature (lag 0) and Nonaccidental Mortality, Adjusted by Individual Pollutant (lag 01) for 9 US Counties

| Pooled | Time-Series Analysis % (95% CI) | Case-Crossover Analysis % (95% CI) |
|---|---|---|
| Apparent temperature | 2.74 (2.01 to 3.48) | 1.78 (1.09 to 2.48) |
| Ozone lag 01 | 2.07 (1.34 to 2.81) | 0.99 (0.31 to 1.68) |
| Match by ozone | — | 1.81 (−0.34 to 4.01) |
| $PM_{2.5}$ lag 01 | 2.76 (1.75 to 3.78) | 1.69 (0.88 to 2.51) |

Percent increases for 5.5°C (10°F).

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**TABLE 4**

Meta-Analysis Results for Various Temperature Definitions and Nonaccidental Mortality for 9 US Counties

| Pooled | Time-Series Analysis % (95% CI) | Case-Crossover Analysis % (95% CI) |
|---|---|---|
| Mean temperature | 3.58 (1.54 to 5.65) | 2.69 (0.84 to 4.57) |
| Minimum temperature | 3.14(1.22 to 5.10) | 2.09 (0.45 to 3.75) |
| Maximum temperature | 2.27 (0.75 to 3.81) | 1.85 (0.39 to 3.34) |
| Temperature >75°F | 2.29 (0.69 to 3.92) | 1.90 (−0.03 to 3.86) |

Percent increases for 5.5°C (10°F).