The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities.

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The Effect of Weather on Respiratory and Cardiovascular Deaths in 12 U.S. Cities

Alfésio L. F. Braga,1,2 Antonella Zanobetti,1 and Joel Schwartz1
1Environmental Epidemiology Program, Harvard School of Public Health, Boston, Massachusetts, USA; 2Environmental Pediatrics Program, University of Santo Amaro School of Medicine, and Laboratory of Experimental Air Pollution, Department of Pathology, University of São Paulo School of Medicine, São Paulo, Brazil

We carried out time-series analyses in 12 U.S. cities to estimate both the acute effects and the lagged influence of weather on respiratory and cardiovascular disease (CVD) deaths. We fit generalized additive Poisson regressions for each city using nonparametric smooth functions to control for long time trend, season, and barometric pressure. We also controlled for day of the week. We estimated the effect and the lag structure of both temperature and humidity based on a distributed lag model. In cold cities, both high and low temperatures were associated with increased CVD deaths. In general, the effect of cold temperatures persisted for days, whereas the effect of high temperatures was restricted to the day of the death or the day before. For myocardial infarctions (MI), the effect of hot days was twice as large as the cold-day effect, whereas for all CVD deaths the hot-day effect was five times smaller than the cold-day effect. The effect of hot days included some harvesting, because we observed a deficit of deaths a few days later, which we did not observe for the cold-day effect. In hot cities, neither hot nor cold temperatures had much effect on CVD or pneumonia deaths. However, for MI and chronic obstructive pulmonary disease deaths, we observed lagged effects of hot temperatures (lags 4–6 and lags 3 and 4, respectively). We saw no clear pattern for the effect of humidity. In hierarchical models, greater variance of summer and winter temperature was associated with larger effects for hot and cold days, respectively, on respiratory deaths. Key words: cardiovascular deaths, nonparametric smoothing, respiratory deaths, temperature, time series, weather. Environ Health Perspect 110:859–863 (2002).

Address correspondence to J. Schwartz, Environmental Epidemiology Program, Department of Environmental Health, Harvard School of Public Health, 665 Huntington Ave., Bldg. I, Room 1414, Boston, MA 02115 USA. Telephone: (617) 384-8752. Fax: (617) 384-8745. E-mail: jschwartz@hsph.harvard.edu

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previous study (7). We modeled the covariates we controlled for (season and trend, day of the week, and barometric pressure) by using nonparametric smoothing as described below.

In environmental epidemiologic studies, we expect the relationship between the outcome and some variables to be nonlinear. The generalized additive model (11) fits smooth functions for these variables. We chose Loess smoothers for our models (12).

In this 8-year study, we used a smooth function of time to capture the basic long time trend represented by the expected six rises and falls in daily deaths over the period because of seasonality (13). This approach has been adopted systematically in environmental epidemiologic studies of daily deaths (6,14–16). Seasonal patterns can vary greatly among cities and for different causes of death. We chose a separate smoothing parameter in each city and for each cause to both eliminate seasonal patterns in the residuals and reduce the residuals of the regression to “white noise” (i.e., remove serial correlation), as described previously (17). In models with remaining serial correlation from the residuals, we incorporated autoregressive terms (18).

The other covariates were barometric pressure on the same day and day of the week. To allow for city- and cause-specific differences, we chose the smoothing parameters for these covariates separately in each location and for each cause to minimize Akaike’s information criterion (19).

Distributed lag models. Distributed lag models have been used extensively in the social sciences (20), and their use in epidemiology was described by Pope and Schwartz (21). Recently, this methodology has been applied to several studies estimating the distributed lag between air pollution and health effects (6,15,22). The motivation for the distributed lag model is the realization that temperature can affect deaths occurring not merely on the same day but also on several subsequent days. Therefore, the converse is also true: deaths today will depend on the “same-day” effect of today’s temperature, the “one-day lag” effect of yesterday’s temperature, and so forth. Therefore, suppressing covariates and just focusing on temperature for the moment, the unconstrained Poisson distributed lag model assumes

$$\log \left[ E(Y) \right] = \alpha + \beta_0 X_t + \ldots + \beta_q X_{t-q} + \epsilon_t,$$  \[1\]

where $X_{t-q}$ is the temperature $q$ days before the deaths. In this study, we examined the effect of temperature in the 12 cities on deaths with latencies (lags) ranging from zero to 20 days after the temperature event. Because the effects of temperature on mortality are usually nonlinear, with J-, U-, or V-shaped relations commonly reported, we used both a linear and a quadratic term for temperature at each lag. Equation 1 can be recast as

$$\log \left[ E(Y) \right] = \alpha + \omega_0 X_t + \ldots + \omega_q X_{t-q} + \omega_q X_t^2 + \ldots + \omega_q X_{t-q}^2 + \epsilon_t,$$  \[2\]

where the $\omega$ are parameters.

Because substantial correlation exists between temperatures on days close together and between temperature and its square, the above regression will have a high degree of collinearity. This will produce unstable estimates of the individual $\omega_i$ and hence poor estimates of the shape of the distribution of the effect over lag.

To gain more efficiency and more insight into the shape of the distributed effect of the temperature over time, constraining $\omega_0$ is useful. If this is done flexibly, substantial gains in reducing the noise of the unconstrained distributed lag model can be obtained, with minimal bias (6). The most common approach is to constrain the shape of the variation of the $\omega_i$ with lag number to fit some polynomial function. We used separate fourth-degree polynomial constraints for the linear and quadratic temperature terms, because that should be flexible enough to encompass any plausible pattern of delayed effect over time. The result is a 10 degree-of-freedom surface of the effect of temperature over the past 3 weeks on death from each specific cause. We simultaneously included linear and quadratic terms for relative humidity up to 20 days before the death in the model, subject to similar constraints.

The immediate effects of weather extremes may represent harvesting—that is, deaths brought forward by only a few days. To assess this, we compared the estimated immediate (lag 0 and 1) effect of hot days with the sum of the estimated effect over 7 days.

By fitting the same model in 12 different locations, for pneumonia, COPD, CVD, and MI deaths, and combining effect size estimates, by lag over the cities, we can estimate the distribution of the effect of temperature and humidity over time. To combine results across cities, we used inverse variance weighted averages including a random variance component to incorporate heterogeneity.

We stratified analysis in two groups of cities: the hot cities (Atlanta, Houston, and Birmingham) and cold cities (Canton, Chicago, Colorado Springs, Detroit, Minneapolis, New Haven, Pittsburgh, and Spokane). As we observed in the total mortality study (7), the differences in the temperature ranges between these two groups of cities preceded a useful combination across all cities.

In this hierarchical study (i.e., a study with multiple levels of analysis), we first fitted a generalized additive Poisson regression for each city and each outcome. In the second stage of the analysis, we fitted an ecologic regression to investigate the role of the prevalence of central air conditioning and the variance of summer and winter temperature, the background mortality rate, percentage of population with a college degree, percent nonwhite, percent unemployed, percent living below the poverty level, city size, and mean age of the population on the estimated effect of hot days (24 hr mean of 30°C) and cold days (24 hr mean of –10°C) on cause-specific deaths. To do this, we regressed the estimated effect in each city at each of those temperatures against the above explanatory variables. We obtained prevalence of air conditioning from the American Housing Survey Web site and the remaining demographic data from the 1990 census. We used inverse variance weighting. Where heterogeneity remained, as assessed by a chi-square test, we fitted the regression including a random variance component, estimated using a maximum likelihood approach, following the method of Berkey et al. (23).

**Results**

Table 1 presents the descriptive analysis of the variables used in the study. The cities varied in | Cities | 1990 population | Deaths* | Temperature* (°C) | Humidity* (%) | Pressure* (mm Hg) |
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<td>Atlanta</td>
<td>1,642,533</td>
<td>36.2</td>
<td>17.1</td>
<td>41.0</td>
<td>36.2</td>
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<tr>
<td>Birmingham</td>
<td>651,525</td>
<td>19.1</td>
<td>16.9</td>
<td>24.9</td>
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<td>Canton</td>
<td>367,885</td>
<td>9.9</td>
<td>10.0</td>
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<td>133.4</td>
<td>25.6</td>
<td>50.0</td>
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<td>Colorado Springs</td>
<td>397,014</td>
<td>8.8</td>
<td>12.5</td>
<td>24.0</td>
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<tr>
<td>Detroit</td>
<td>2,111,997</td>
<td>58.6</td>
<td>10.5</td>
<td>49.0</td>
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<td>Houston</td>
<td>2,518,199</td>
<td>47.0</td>
<td>20.3</td>
<td>54.0</td>
<td>92.0</td>
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<tr>
<td>Minneapolis</td>
<td>1,518,196</td>
<td>32.3</td>
<td>11.3</td>
<td>45.0</td>
<td>89.7</td>
</tr>
<tr>
<td>New Haven</td>
<td>804,219</td>
<td>20.4</td>
<td>10.7</td>
<td>43.0</td>
<td>66.6</td>
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<td>Pittsburgh</td>
<td>1,336,649</td>
<td>42.4</td>
<td>5.0</td>
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<td>69.3</td>
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<td>Seattle</td>
<td>1,507,319</td>
<td>29.3</td>
<td>11.4</td>
<td>32.0</td>
<td>77.0</td>
</tr>
<tr>
<td>Spokane</td>
<td>361,364</td>
<td>8.7</td>
<td>5.6</td>
<td>22.8</td>
<td>80.0</td>
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*Daily mean temperature. \(a\)Relative humidity. \(b\)Barometric pressure.
size, although in 1990 seven cities of the study had more than one million inhabitants. We divided the cities into two groups according to their meteorologic characteristics: hot (Atlanta, Birmingham, and Houston) and cold (Canton, Chicago, Colorado Springs, Detroit, Minneapolis, New Haven, Pittsburgh, and Spokane). Among the hot cities, Houston was the hottest and most humid; among the cold cities, Minneapolis was the coldest and had the widest range of temperatures. Seattle, located in the extreme northwest of the United States, had the narrowest range of temperatures of the cities in this study and rarely exhibited extreme temperatures.

In the hot cities and in New Haven, temperature was positively associated with humidity. Correlations between temperature and barometric pressure were, in general, small and negative.

We estimated the covariate-adjusted (including humidity) effects of temperature on respiratory and CVD daily deaths by lag in the 12 cities, using a standard range of temperatures. We then performed a meta-analysis of the 12 cities, using a standard range of temperatures for extreme temperatures are not similar (22). We have focused our attention on exploring the lag structure between temperature and daily deaths using a systematic approach to look at the delayed effects of weather on mortality up to 3 weeks afterwards. In this study we looked at the temperature effect on cause-specific deaths in 12 U.S. cities. As observed in the total mortality study (7), hot and cold temperatures were associated with increased deaths, and the shape of this relationship varied according to climatic characteristics of the cities. However, we found sizable effects of temperature on daily deaths just at lag 0. We found lagged effects of hot temperatures in the cold cities and specifically for MI and COPD, and in cold cities for pneumonia.

In cold cities, we found differences in terms of temperature effect on CVD. Although both hot and cold temperatures affected MI and total CVD deaths, the relative impacts of the extreme temperatures were different. Cold presented more homogeneous and persistent effects on both outcomes, with no evidence of harvesting. Heat presented a much more important effect on MI deaths than it did on CVD deaths. These effects were predominantly short-term mortality displacement. The pattern observed for temperature effects on CVD deaths in cold cities is similar to those observed for total deaths, probably because most of the total mortality is due to CVD deaths.

Cold temperatures did not have much effect on respiratory mortality in cold cities. However, heat increased respiratory deaths.

Figure 1. Overall effect of temperature (°C) on MI (A), CVD (B), pneumonia (C), and COPD (D) daily deaths in the eight cold cities: Canton, Colorado Springs, Chicago, Detroit, Minneapolis, New Haven, Pittsburgh, and Spokane. In the z-axis, a log relative risk of 0.1 represents a 10% increase in mortality.
For COPD, the heat effect was remarkable and acute (lag 0, 25-fold higher than the cold effect), whereas we observed a lagged effect for pneumonia.

In hot cities, we found no relevant effects of cold on both respiratory death and CVD deaths. When we analyzed pneumonia, we observed no association with temperature. The same behavior could be seen for CVD. However, for the relation between heat and both MI and COPD deaths, we saw a pattern different from the total mortality results: We observed lagged effects for these two causes of death. Hence, even in hot cities, where people are more accustomed to hot temperatures and air conditioning is common (26), the effect of heat on health, leading to increased deaths, can overcome adaptive mechanisms.

In our hierarchical model, we found that the variance of summer and winter temperature was associated with substantial changes in the effects of hot and cold days on respiratory but not CVD deaths. The substantial mortality increase in cities with more variable temperature suggests that increased temperature variability is the most relevant change in climate for the direct effects of weather on respiratory mortality.

In many ways, the results of this study and our previous study of total mortality parallel those of the Eurowinter study (27), which assessed the association between daily deaths and temperature in the winter in eight European regions. Daily deaths increased with falling temperatures in all regions. However, the effect of a cold day was greater in warmer climates than in colder climates. In our 12-city U.S. studies, the converse was true: The effect of hot days was worse in cities where they were less common. In the Eurowinter study, the effect of cold days was reduced by warmer temperatures in the living room and more hours per day of heat in the bedroom—that is, by greater use of space conditioning to reduce exposure to the cold weather. In our study, greater use of central air conditioning was associated with a reduced effect of hot days for total and for cause-specific mortality, although the results were less significant for the cause-specific mortality. Greater variability in either summer or winter temperatures, which might be expected to reduce protective behavior such as always wearing hats, was associated with increased effects of cold or heat waves. The overall message seems to be that space conditioning and behavior can substantially modify the adverse impacts of temperature extremes, but that this behavior is more frequently found in the climates where those extremes are common.

We found no association in the second-stage analysis with baseline mortality rates or social or demographic factors. However, a log-linear regression builds in interactions by design—that is, we estimated our temperature effect as a relative or percentage change in each city. In cities with a higher baseline rate, a greater absolute effect is built in. The second-stage regression therefore tests supermultiplicativity. This makes the failure to find interactions with direct or indirect markers of baseline risk understandable and the association with the temperature variances more impressive.

In the present study and in the previous one (7), we have used mean temperature. The best indicator of the temperature effect on health is still debated (2). Further analysis using different parameters (e.g., minimum temperature and dew point temperature) are needed to compare the results presented here and elsewhere, and for finding the best instrument for estimating the health effect due to extreme weather exposure.

In this cause-specific death study, we saw no consistent patterns for the relation of humidity to daily deaths by city. The combined city estimate reinforced this idea, showing no overall effect of humidity on total daily deaths. Using dew point temperature can give a more reasonable estimate of the humidity effect on daily deaths and should be pursued in the future.

Air pollution is a predictor of daily deaths. Effect modification was tested by Samet et al. (26) in a study of 20 years of data in Philadelphia. They stratified days into 20 categories based on synoptic weather conditions and found no effect modification. This does not preclude the possibility that effect
moderation may be seen in other studies. However, the only air pollutant consistently associated with daily deaths in the U.S. is airborne particles (28). Unfortunately, airborne particles are measured only one day in six in most U.S. cities. This would prevent us from examining the effect of multiple lags of weather in our study. Hence, we have chosen not to include it in our models.

In summary, we found that temperature is associated with increased daily cause-specific deaths in both cold and hot cities. In cold cities, both heat and cold contributed with daily cause-specific deaths. In hot cities, only heat presented important effect on daily deaths, and its effect was smaller than those observed in cold cities. In these cities, people seem to be more adapted to heat waves and also are not exposed to very low temperatures. Therefore, we reinforce the concept that analysis of the impact of any climatic change should take into account regional weather differences and that further analysis using different weather indicators must be done.

REFERENCES AND NOTES