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The Time Course of Weather-Related Deaths

Alfésio Luís Ferreira Braga,^{1,2,3} Antonella Zanobetti,¹ and Joel Schwartz¹

We carried out time-series analysis in 12 U.S. cities to estimate both the acute effects and the lagged influence of weather on total daily deaths. We fit generalized additive Poisson regressions for each city using nonparametric smooth functions to control for long time trend and barometric pressure. We also controlled for day of the week. We estimated the effect and the lag structure of both temperature and humidity on the basis of a distributed lag model. In cold cities, both high and low temperatures were associated with increased 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 immediately preceding day and was twice as large as the cold effect. The hot temperature effect appears to be primarily harvesting. In hot cities, neither hot nor cold temperatures had much effect on deaths. The magnitude of the effect of hot temperature varied with central air conditioning use and the variance of summertime temperatures. We saw no clear pattern for humidity effect. These dissimilarities indicate that analysis of the impact of any climatic change should take into account regional weather differences and harvesting. (EPIDEMIOLOGY 2001;12:662–667)

Keywords: total deaths, time series, temperature, humidity, distributed lag, meta-analysis.

The association between extremes of temperature and deaths is well known.¹ An excess of deaths is observed during both winter and summer. Extreme high temperatures have been related with deaths among the elderly and young children,² and a threshold temperature has been sometimes postulated.^{3,4} Other studies have reported nonlinear U-, J-, or V-shaped associations without thresholds. In the winter, death rates are usually higher than in the summer. The range of contributing factors usually present during the winter, however, such as respiratory infections and air pollutant peaks, make a precise estimate of the amount of that excess that is attributable to cold temperatures difficult.⁵

The increase in greenhouse gas concentrations over the last century is expected to increase both mean temperatures and the variability of temperatures. Hence, a better understanding of the acute effects of temperature on human mortality remains a major goal. Different

approaches have been used in past analyses to examine the influence of temperature on daily deaths. Linear terms for daily measures of temperature, on the same or lagged days, or lagged moving averages, have been applied in many studies.^{6–8} Nonlinear terms also have been used.^{9,10} Kalkstein *et al.*,¹¹ using factor analysis, proposed grouping meteorologic factors, creating categories of meteorologic variables. Pope and Kalkstein¹² applied this synoptic approach to a time-series study of air pollution and daily mortality. Samet *et al.*,¹³ using daily deaths in Philadelphia, provided a comparative analysis of these methods, reporting that the use of synoptic categorization of weather was inferior to the inclusion of either parametric or smoothed terms to control for weather. In any event, the lag structure between weather and daily deaths has been little explored. Different lag structures have been used, but not systematically examined. Temperatures of the same day and the day before have been used separately¹⁴ or as lagged moving averages.⁷ Others have explored extended lags, such as terms for temperatures of the three previous days.⁸ Choices are usually made *a priori* or on the basis of model adjustment parameters rather than on biological plausibility, and this omission has been a common limitation for researchers.

We previously applied the distributed lag model to estimate a more biologically plausible lag structure between air pollution and deaths in ten U.S. cities.¹⁵ In this study, we prespecified an amount of time we felt would be sufficient to capture the acute effects of weather, and explored the lagged influence of temperature and humidity on total daily deaths in 12 U.S. cities.

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FIGURE 1. Geographical localization of the 12 cities analyzed in this study.

Subjects and Methods

DATA

Daily counts of total deaths in the metropolitan counties containing Atlanta, GA; Birmingham, AL; Canton, OH; Chicago, IL; Colorado Springs, CO; Detroit, MI; Houston, TX; Minneapolis-St. Paul, MN; New Haven, CT; Pittsburgh, PA; Seattle, WA; and Spokane, WA, were extracted from National Center for Health Statistics mortality tapes for the years 1986 through 1993 (Figure 1). Minneapolis and St. Paul were combined and treated as one city. Deaths due to external causes (*International Classification of Diseases*, 9th revision, 800–999) were excluded.

Daily weather data were obtained from the nearest airport station (EarthInfo CD, National Climatic Data Center, Surface Airways; EarthInfo, Boulder, CO).

METHODS

We modeled counts of daily deaths in a Poisson regression. Our models for daily deaths contained two components. For temperature and relative humidity, we fit models examining the effects out to lags of 3 weeks before the event, which we believe should be sufficient to capture any delayed effects. The covariates we controlled for, that is, season, day of the week, and barometric pressure, were accounted for by using nonparametric smoothing as described below.

The generalized additive model¹⁶ allows variables expected to have a nonlinear effect on the outcome to be modeled using smooth functions, which are generalizations of moving averages. Because seasonal patterns are expected to show six rises and falls in daily deaths over the 6 years of study, we used a smooth function of time to capture this pattern.¹⁷ This approach has become standard in studies of daily deaths.^{14,15,17,18}

The purpose of the smooth function of time is to remove the basic long-term pattern from the data. Seasonal patterns can vary greatly between, for example, Birmingham and Spokane, and we chose a separate smoothing parameter in each city to both eliminate

seasonal patterns in the residuals and reduce the residuals of the regression to “white noise”¹⁹ (that is, remove serial correlation). We used this approach because each death is an independent event, and autocorrelation in residuals indicates that there are omitted, time-dependent covariates the variation of which may confound temperature and humidity variables. If the autocorrelation is removed, remaining variation in omitted covariates has no systematic temporal pattern, and hence confounding is less likely. This approach has been described previously.¹⁹ When necessary, we incorporated autoregressive terms²⁰ to eliminate serial correlation from the residuals.

The other covariates were barometric pressure on the same day and day of the week. To allow for city-specific differences, we chose the smoothing parameters for these covariates separately in each location to minimize Akaike’s information criterion.²¹

DISTRIBUTED LAG MODELS

Distributed lag models have been extensively used in the social sciences,²² and their use in epidemiology was described by Pope and Schwartz.²³ We have recently applied this methodology to estimating the distributed lag between all-cause mortality and air pollution in 10 U.S. locations.¹⁵ The motivation for the distributed lag model is the realization that temperature can affect not merely deaths occurring on the same day, but 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, etc. Therefore, suppressing covariates and just focusing on temperature for the moment, the unconstrained Poisson distributed lag model assumes:

$$\text{Log}[E(Y_t)] = \alpha + \beta_0 X_t + \dots + \beta_q X_{t-q} + \varepsilon_t \quad (1)$$

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 0 until 20 days before the death. 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. Eq 1 can be recast as:

$$\begin{aligned} \text{Log}[E(Y)] = & \alpha + \omega_0 X_t + \dots + \omega_q X_{t-q} + \omega_{q+1} X_t^2 + \dots \\ & + \omega_{q+q} X_{t-q}^2 + \varepsilon_t \quad (2) \end{aligned}$$

where the ω_i values are parameters.

Because there is substantial correlation between temperatures on days close together and between temperature and its square, the above regression will have a high degree of collinearity. This collinearity will result in unstable estimates of the individual ω_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, it is useful to constrain the ω_i . If this is done

TABLE 1. The Populations and the Descriptive Analysis of the Variables in the Study in the 12 Locations

Cities	1990 Population	Deaths	Temperature* (°C)			Humidity† (%)			Pressure‡ (mmHg)
			5%	Mean	95%	5%	Mean	95%	
Atlanta	1,995,605	36.2	3.3	17.1	28.3	41.0	67.0	93.0	736
Birmingham	839,942	19.1	2.8	16.9	27.8	49.0	70.5	91.0	747
Canton	367,585	9.9	-6.1	10.0	24.4	51.0	73.7	93.0	729
Chicago	5,105,067	133.4	-7.2	10.1	25.6	50.0	70.8	92.0	744
Colorado Springs	397,014	6.0	-6.1	9.5	22.8	25.0	51.0	84.0	610
Detroit	2,111,687	59.7	-6.1	10.5	25.6	49.0	69.2	89.0	744
Houston	2,818,199	47.0	7.2	20.3	30.0	54.0	75.0	92.0	760
Minneapolis-St. Paul	1,518,196	32.3	-13.3	7.9	25.0	45.0	68.7	90.0	739
New Haven	804,219	20.4	-6.1	10.7	25.0	43.0	66.8	92.0	760
Pittsburgh	1,336,449	42.4	-5.0	11.2	25.0	48.0	69.3	90.0	732
Seattle	1,507,319	29.3	2.8	11.4	20.6	52.0	77.0	93.0	752
Spokane	361,364	8.7	-5.6	8.8	22.8	35.0	68.0	95.0	699

* Daily mean temperature.

† Relative humidity.

‡ Barometric pressure.

flexibly, substantial gains in reducing the noise of the unconstrained distributed lag model can be obtained, with minimal bias.¹⁵ The most common approach is to constrain the shape of the variation of the ω_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. Linear and quadratic terms for relative humidity up to 20 days before the death were also included in the model, subject to similar constraints.

By fitting the same model in 12 different locations, and combining effect size estimates, by lag over the cities, we can obtain an estimate of 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.

The existence of heterogeneity would suggest that there are differences in the effects of weather across the cities. Understanding the sources of that heterogeneity is important. To explore this we used two approaches. First we examined stratification of the cities by climatic characteristics. Second, we used a hierarchical model to examine how the expected risk of deaths on a hot day (mean = 30°C) varied with the variance of the summer temperature and the air conditioning prevalence in each city. This modeling was done by fitting an ecologic regression

$$\hat{\beta}_i = \alpha_0 + \alpha_1 Z_i + \varepsilon_i \quad (3)$$

where $\hat{\beta}_i$ is the estimated log relative risk of 30°C in city i and Z_i is the explanatory variable in city i . Inverse variance weighting was used.

Results

Table 1 presents the descriptive analysis of the variables in the study. Houston was the warmest city and also had a high relative humidity. Minneapolis-St. Paul, on the other hand, presented the widest range of temperatures

and also was the coldest one. The smallest variation of temperature was observed in Seattle.

Table 2 presents the correlation coefficients between temperature and other weather variables. Temperature and humidity were negatively correlated in most of the cities, excepting Birmingham and New Haven. Spokane and Seattle presented the biggest negative correlations. Except in Colorado Springs, where a positive correlation was observed between temperature and barometric pressure, these two variables presented small and negative correlations.

We estimated the covariate-adjusted (including humidity) effect of temperature on daily deaths by lag in the 12 cities, using a standard range of temperatures. In general, cold temperatures were associated with increased deaths on the same day. This effect declined but remained positive for several subsequent days. In some of the cities, the effect of temperature declines rapidly, as can be seen in Atlanta, Birmingham, New Haven, and Seattle. On the other hand, the decline of the effect extended for 1 or 2 weeks in Houston, Detroit, and Spokane. The size of the effect also varies among the cities. The highest effect was observed for cold temperature on the same day of the death in Seattle, whereas the smallest effect was observed in Colorado Springs and

TABLE 2. Pearson Correlation Coefficients between Temperature and Humidity and Barometric Pressure in the Counties of the Study

Cities	Humidity (%)	Pressure (mmHg)
Atlanta	0.14	-0.20
Birmingham	0.18	-0.38
Canton	-0.11	-0.11
Chicago	-0.14	-0.27
Colorado Springs	-0.39	0.26
Detroit	-0.15	-0.20
Houston	0.12	-0.58
Minneapolis-St. Paul	-0.20	-0.33
New Haven	0.25	-0.20
Pittsburgh	-0.06	-0.11
Seattle	-0.44	-0.10
Spokane	-0.75	-0.22

FIGURE 2. Overall effect of temperature on daily deaths in 12 cities (A), in the three hottest cities, Atlanta, Birmingham, and Houston (B), and in the eight coldest cities, Canton, Chicago, Colorado Springs, Detroit, Minneapolis-St. Paul, New Haven, Pittsburgh, and Spokane using both a common (C) and a compressed (D) temperature scale. Note that the lag zero effect is on the right hand side of the figure. A, Effect of temperature on daily deaths in 12 cities. B, Effect of temperature on daily deaths in hot cities. C, Effect of temperature on daily deaths in cold cities. D, Effect of temperature on daily deaths in cold cities (compressed scale).

Minneapolis-St. Paul. Although it was small in some of the cities, the effect of cold was present in all of them.

The effect of hot temperatures was restricted to the same day or the following day. In five of the cities (Atlanta, Birmingham, Houston, New Haven, and Seattle) there were negative or no effects for hot temperatures. In Colorado Springs, Canton, Detroit, Chicago, and Spokane, the positive effect observed at lag 0 was followed by a period of lower-than-average deaths, returning to the base line after a few days. This pattern is sometimes referred to as the harvesting effect, and was not seen for the effect of cold weather.

In Spokane, hot and cold temperatures presented effects on daily deaths with the same magnitude, a characteristic that was not observed in any other city.

Figure 2 presents the meta-analysis of temperature effect for the 12 cities (A), three hot cities (B), and eight cold cities, with the same scale of log relative risk used for the previous plots (C), and with a compressed scale (D), allowing a detailed visualization of its pattern. Seattle was not included in this stratified analysis by tem-

perature groups because its mild temperature range did not fit in either group. When the 12 cities were analyzed together, the magnitude of hot and cold temperature effects were almost the same (4% increase in daily deaths for hot days and 3% for cold days). The effects of hot, but not cold, weather appeared to be primarily harvesting. Very low temperatures, however, are rare in hot cities, and none of these presented temperatures below -13°C . In the separate analysis of the three hottest cities (Atlanta, Birmingham, and Houston), we adopted a range of temperature that was common to those cities, and neither hot nor cold temperatures had much effect on deaths. When the coldest cities (Canton, Chicago, Colorado Springs, Detroit, Minneapolis-St. Paul, New Haven, Pittsburgh, and Spokane) were analyzed, both hot and cold temperatures were positively associated with deaths on the same day, with hot effect being twice as large the cold effect. The increase on hot days appeared predominantly harvesting. The effect of cold weather, in contrast, remained positive for several weeks with no sign of a rebound.

TABLE 3. Coefficients and Standard Errors of the Association between the Log Relative Risk of Deaths at 30°C and Two Explanatory variables: Prevalence of Central Air Conditioning use and Variance of Summertime Temperatures in Each City

	Coefficients	Standard Errors
Air conditioning	-0.0016	0.0007
Variance of summertime temperatures	0.0031	0.0007

We estimated the effect of humidity on daily deaths in the 12 cities. There is no clear pattern for the effect of humidity on daily deaths, neither in terms of lag structure nor in terms of differences between high and low humidity.

In our overall estimate of the relative humidity effect on daily deaths, we found no evidence of a consistent effect of humidity. Stratifying the cities by weather characteristics also did not suggest any patterns.

In hierarchical models, we found an inverse association between the expected log relative risk of death at 30°C and the prevalence of central air conditioning use in the city (Table 3 and Figure 3). When the variance of summertime temperatures was used as explanatory variable, we found a positive association (Table 3 and Figure 4). The variance of summertime temperature explained more (64%) of the variation in the log relative risk on hot days than the use of air conditioning (33%).

Discussion

The effect of temperature on daily deaths has attracted increased attention and motivated many studies about the shape of this relation.^{1,2} In the present study we used a systematic approach to look at the delayed effects of weather on mortality up to 3 weeks afterward and applied it to a dozen cities. Hot and cold temperatures were associated with increased deaths, but the shape of this relation varied according to climatic characteristics of the cities.

FIGURE 3. Log relative risk of total deaths at 30°C according to the prevalence of central air conditioning use.

FIGURE 4. Log relative risk of total deaths at 30°C according to the variance of summertime temperatures.

Consistently across all the cities, the largest effect of temperature on daily deaths was lag 0. The "J" shape was the most common behavior for the temperature effect, and an adaptive mechanism seems to define which temperature contributes more to increase total deaths. In Canton, Chicago, Colorado Springs, and Minneapolis-St. Paul, hot temperatures had the largest initial effects on daily deaths. This result is not unexpected, as these hot temperatures are rare events in those cities, making adaptation less likely.²⁴ Nevertheless, this effect appeared to be predominantly short-term mortality displacement. The effect of cold temperatures was muted, as might be expected in locations where the population is more adapted to low temperatures.²⁵ It was persistent, however, with no evidence of a rebound period of lower mortality. In Spokane, Pittsburgh, and to a lesser extent Detroit, U shapes were observed at lag 0, showing similar increases in deaths under both high and low temperatures.

We worked with cities that present a wide range of temperatures. Whereas the range of the 95th percentile of temperatures among the cities was around 10°C (30°C in Houston and 20.6°C in Seattle), the range of the 5th percentile of temperatures was 20°C (7.2°C in Houston and -13.3°C in Minneapolis-St. Paul). Estimates of the effect of hot days based on a standard range of temperature seemed reasonable. It was difficult, however, to specify a common range of cold temperatures that did not truncate the curves in some cities or extrapolate to unobserved temperatures in others. This difficulty motivated our stratifying the analysis into hot and cold cities.

The lack of association between temperature and daily deaths in Atlanta, Birmingham, and Houston, seen in the hot-city meta-analysis, suggested that the inhabitants of these cities are more adapted to high temperatures, probably owing to physiologic acclimatization and the high penetration of air conditioning in those cities (81%, 70%, and 79%, respectively).²⁶ In addition, they have not been exposed to very low temperatures. This

result is similar to that reported by Keatinge *et al*²⁷ in a cross-sectional study in Europe.

We found that the risk of death on the hot days increases with increasing variation in the summertime temperatures. This finding is of potential public health significance, as predictions for global climate change in the 21st century all suggest that temperature variability will increase. Thus, although we find that there is acclimatization to higher *mean* temperatures, with a little impact in hot cities, we do not see any acclimatization to increases in temperature variability.

In contrast to the effects of temperature, we found no consistent pattern for the relation of humidity to daily deaths. The patterns in the 12 cities differed too substantially to allow us to identify main characteristics and could be due to chance. The combined city estimate reinforced this idea, showing no overall effect of humidity on total daily deaths.

Our choice of looking at effects of temperature out to a 20-day lag was motivated by our belief that this lag was sufficient to capture the acute effects of weather. The distributed lag model does not force this conclusion, however, and a pattern of elevated mortality risk at the longest lag period would be evidence for the need to consider longer lags. The results shown in Figure 2 suggest that 21 days were more than sufficient, and that a 14-day lag would probably suffice.

We treated barometric pressure as just another covariate in the models because we thought that with 10 degrees of freedom per variable, we had too much collinearity to fit a three-variable distributed lag model. Also, temperature and humidity are the traditional weather parameters that have been examined, and are where evidence of lagged effects exists. Only recently has anyone looked at pressure, and we felt that including that only on 1 day was reasonable. In summary, we showed that temperature is associated with increased daily deaths mainly in cold cities, and that hot temperatures have a more immediate effect when compared with cold. In terms of public health impacts, however, the effects of cold temperatures appear to be more important, as they do not appear to be short-term mortality displacement. This conclusion is consistent with results of earlier studies.^{25,27} Nevertheless, we report this here in an analysis of daily data in multiple locations. In hot cities, people seem to be more adapted to heat waves and also are not exposed to very low temperatures. Therefore, analysis of the effect of any climatic change should take into account regional weather differences.

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