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Changing patterns of the temperature–mortality association by time and location in the US, and implications for climate change

Francesco Nordio [a,b], Antonella Zanobetti [b], Elena Colicino [b], Itai Kloog [c], Joel Schwartz [b,*]

[a] TIMI Study Group, Division of Cardiovascular Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA
[b] Department of Environmental Health, Exposure, Epidemiology, and Risk Program, Harvard School of Public Health, Boston, MA, USA
[c] Department of Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, Israel

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The shape of the non-linear relationship between temperature and mortality varies among cities with different climatic conditions. There has been little examination of how these curves change over space and time. We evaluated the short-term effects of hot and cold temperatures on daily mortality over six 7-year periods in 211 US cities, comprising over 42 million deaths. Cluster analysis was used to group the cities according to similar temperatures and relative humidity. Temperature–mortality functions were calculated using B-splines to model the heat effect (lag 0) and the cold effect on mortality (moving average lags 1–5). The functions were then combined through meta-smoothing and subsequently analyzed by meta-regression. We identified eight clusters. At lag 0, Cluster 5 (West Coast) had a RR of 1.14 (95% CI: 1.11,1.17) for temperatures of 27 °C vs 15.6 °C, and Cluster 6 (Gulf Coast) has a RR of 1.04 (95% CI: 1.03,1.05), suggesting that people are acclimated to their respective climates. Controlling for cluster effect in the multivariate-meta regression we found that across the US, the excess mortality from a 24-h temperature of 27 °C decreased over time from 10.6% to 0.9%. We found that the overall risk due to the heat effect is significantly affected by summer temperature mean and air condition usage, which could be a potential predictor in building climate-change scenarios.

1. Introduction

The relationship between temperature and non-accidental mortality with subsequent identification of vulnerable populations at risk is currently being investigated by public health specialists worldwide (Analitis et al., 2008; Anderson and Bell, 2011; Basu and Ostro, 2008; Medina-Ramón and Schwartz, 2007; Zanobetti et al., 2012a, 2012b). The nature of this relationship varies depending on the geographical location and socio-economic status of affected populations (Braga et al., 2001; Hajat and Kosatky, 2010; Yu et al., 2010). A key issue is what dose–response curve to use for the acute effects of temperature in estimating the potential impacts of climate change.

Some studies have assumed that the dose–response relationship will stay constant over time (Peng et al., 2011; Voorhees et al., 2011). However, cross-sectional observations contradict this in finding. In US cities that are currently warmer in the summer, higher temperatures are needed to produce the same percentage increase in mortality as occurs at less extreme temperatures in locations with milder climates. One could alternatively choose to assess the effect of e.g., a 2 °C increase in mean temperature in one city by using a dose–response curve from a city that has already attained that temperature. However that assumes fairly rapid acclimatization to the new temperature régime, and the cross-sectional data provides no information on how likely that is. Clearly a more detailed assessment of how dose–response curves vary by temperature régime and how fast they change is needed to provide reasonable estimates of future risk.

A small number of studies have addressed this question. For example, in a recent paper, Deschênes and Greenstone estimated the impacts of climate change on mortality and expenditures on self-protection or adaptation using economic models. Their measure of self-protection is energy consumption, which via air conditioning (AC) is perhaps the primary form of protection against high temperatures. Their identification strategy relied on the presumed random year-to-year local variation in temperature (Deschênes and Greenstone, 2011), but does not address acute episodes. Using an econometric model, Barreca et al. found that the mortality effect of an extremely hot day declined by approximately 80% between 1900–1959 and 1960–2004 in the United States (Barreca et al., 2013). However, that analysis was conducted at the state level, and with only monthly mortality statistics. Cunrui Huang et al. (2011) recently wrote an extensive review about projecting future heat-related mortality under climate change scenarios. In their

* Corresponding author at: Department of Environmental Health, Department of Epidemiology, 665 Huntington Avenue, Landmark Center Room 415, Boston, MA 02115, USA.

E-mail address: jschwrtz@hsph.harvard.edu (J. Schwartz).

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conclusion they identified that significant differences in projected mortality can be found in different emission scenarios, suggesting that greenhouse gas mitigation policies are important for protecting human health. They also acknowledged that further research is needed to provide a stronger theoretical framework for these types of projections, including better understanding of socioeconomic development, adaptation strategies and land-use patterns. The approaches commonly used in environmental epidemiology to study these effects are city-specific time series or case-crossover analysis (Braga et al., 2001; Curriero et al., 2002). In these previously published studies, if temperature was estimated as a linear term both methods produce a parameter that expresses the logarithm of the incidence rate ratio after control for confounders, for each city included in the study. Coefficients from multiple cities can be combined into a single aggregate parameter using a univariate meta-analysis (Stieb et al., 2002). However, complex associations including nonlinear J- or U-shaped relationships between temperature and mortality are usually described with functions defined by multiple parameters, and thus require more sophisticated meta-analytical approaches capable of handling the multivariate nature of the summary estimates. Moreover understanding drivers of change in response over time and adequate power for meta-regression requires more years of follow-up and more locations than have generally been reported (Gasparrini et al., 2012). Åström et al. (2013) recently analyzed the relationship between extreme hot/cold temperatures and all-cause mortality, stratified by decade, sex, and age from 1901 to 2009 in Sweden. The paper focused exclusively on extreme temperatures. Specifically, the authors looked at changes in the effect above 98th percentile and below the 2nd percentile of temperature over time, and only in Stockholm. Interestingly, they found that the relative risk of total daily mortality due to heat extremes in all decades decreased linearly over time; decline in mortality with cold extremes over time was not found. Bobb et al. (2014) recently examined heat-related mortality and found that the mortality risk decreased over time supporting the hypothesis that the population is continually adapting to heat. Also Guo and co-authors in their systematic evaluation recently reported that people have some ability to adapt to their local climate type, but both cold and hot temperatures are still associated with increased risk of mortality (Guo et al., 2014).

In this study we examine the association between temperature and mortality over six 7-year periods in 211 cities in the United States, focusing particularly on changes over time, and across cities clustered by common weather patterns. Our study is not looking at extreme effects, but continuous effects of temperature, and more cities and for a longer time period than previous studies in the U.S.

We also explore the role of land use, air conditioning, etc. in predicting these changes. Several approaches to combining nonlinear curves have been proposed. Schwartz and Zanobetti proposed a method they called meta-smoothing that combined estimated effects at a series of exposures across multiple locations (Schwartz and Zanobetti, 2000). Alternative methods involved combining coefficients at the knot points of splines, an approach recently updated and implemented in R through the mvmeta function (Gasparrini et al., 2012). A disadvantage of this approach is that it is difficult to put the knot points at the same temperatures in cities with a wide range of climates, as in the US. To address this we initially identified clusters of cities with similar values of temperature and relative humidity and then created a large pooled exposure–response curve for each cluster. We subsequently studied how these curves changed over time and space from 1962 to 2006. Finally, using the same mvmeta function used for meta-smoothing to assess temperature risk on mortality, we performed a multivariate meta-regression analysis to assess how the risk estimates vary with potential meta-predictors, such as climatic and socio-economic variables, measured at the city level. This type of strategy could allow us to build a model to predict future fatalities, influenced by climate change in different US climate zones.

2. Material and methods

2.1. Mortality data

We selected 211 US cities that had complete mortality and daily temperature (monitors that have at least 98% of the observations available) data with a nationwide geographic distribution (Fig. 1). Analyses were conducted at the city level, which in most cases was restricted to a single county. However, we used multiple counties where the city's population extends beyond the boundaries of one county. Individual mortality data was obtained from the National Center for Health Statistics (NCHS) and from state public health departments. Data from 1967 to 1973 were not available because NCHS did not obtain date of death in those years. 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). Overall, 42,471,868 deaths were included in the study.

2.2. Environmental data

Meteorological measurements were obtained from the airport weather stations nearest to each county, including daily mean temperature, wind speed, sea level pressure, visibility and dew point (National Oceanic and Atmospheric Administration [NOAA]). Relative humidity was calculated with the following formula:

$$RH = 100\left(\frac{112-0.1T_a+T_d}{112+0.9T_a}\right)^8$$

where T_a represents air temperature and T_d represents dew point temperature (Wanielista, 1990). For days of the year where monitors had missing data, we used the values of the nearest monitor within 60 km.

2.3. Socioeconomic and land use data

Because we are interested in factors which could potentially modify the association with temperature and particularly ones that might be modifiable, we have obtained data on socioeconomic, land use, and other factors. From the U.S. Census Summary File 3 downloaded from Social Explorer, we obtained population density, proportion of the population below poverty level, proportion of the population over 25 years of age (25+) who completed college, proportion of the population 25+ who did not complete high school, and proportion of black population for the 1960–2000 decennial censuses. Median family income in dollars for every ten years from 1959 to 1999 was obtained from the US Census Historical Income Tables for Counties (http://www.census.gov/hhes/www/income/data/historical/county/). From the 1992 and 2001 National Land Cover datasets, available from the Multi-Resolution Land Characteristics Consortium (MRLC) and the Enhanced Historical Land Use, and Land Cover Data for 1970–1985 from the US Geological Survey (USGS 1986), we calculated proportion of land with green surface by county for three time periods. Green land uses include agriculture, forests, wetlands and grasslands. Census and land use data were merged to individuals based on their county of residence, we estimated percentage of households in each city with central air conditioning (AC) in 1970, 1980, 1990, and 2000 using available county level or metropolitan area level data. 1970 and 1980 county level AC data come from the US Census of Population. For later years metropolitan area data from the American Housing Survey (AHS) was used. 1990 and 2000 estimates were based on linearly interpolating data from available years which vary by city. For cities not included in the AHS, the nearest metropolitan area with available data was used. For northern New England cities, regional level data from the US Energy