Environmental Research 161 (2018) 464–471

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Accounting for adaptation and intensity in projecting heat wave-related mortality

Yan Wang[a], Francesco Nordio[b], John Nairn[c,d], Antonella Zanobetti[a], Joel D. Schwartz[a,*]

[a] *Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA*
[b] *Department of Medicine, Brigham and Women's Hospital, Boston, MA, USA*
[c] *Australian Bureau of Meteorology, Adelaide, South Australia, Australia*
[d] *University of Adelaide, Adelaide, South Australia, Australia*

ARTICLE INFO

Keywords:
Heat wave
Mortality
Adaptation
Intensity
Projection

ABSTRACT

Background: How adaptation and intensity of heat waves affect heat wave-related mortality is unclear, making health projections difficult.
Methods: We estimated the effect of heat waves, the effect of the intensity of heat waves, and adaptation on mortality in 209 U.S. cities with 168 million people during 1962–2006. We improved the standard time-series models by incorporating the intensity of heat waves using excess heat factor (EHF) and estimating adaptation empirically using interactions with yearly mean summer temperature (MST). We combined the epidemiological estimates for heat wave, intensity, and adaptation with the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset to project heat wave-related mortality by 2050.
Results: The effect of heat waves increased with its intensity. Adaptation to heat waves occurred, which was shown by the decreasing effect of heat waves with MST. However, adaptation was lessened as MST increased. Ignoring adaptation in projections would result in a substantial overestimate of the projected heat wave-related mortality (by 277–747% in 2050). Incorporating the empirically estimated adaptation into projections would result in little change in the projected heat wave-related mortality between 2006 and 2050. This differs regionally, however, with increasing mortality over time for cities in the southern and western U.S. but decreasing mortality over time for the north.
Conclusions: Accounting for adaptation is important to reduce bias in the projections of heat wave-related mortality. The finding that the southern and western U.S. are the areas that face increasing heat-related deaths is novel, and indicates that more regional adaptation strategies are needed.

1. Introduction

The Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) states that there is medium confidence that heat waves, defined as consecutive days of extreme high temperature, have become more frequent and longer-lasting globally in the second half of the 20th century, and that this trend is very likely to continue in the 21st century (IPCC, 2013). The associations between heat waves and increased mortality have been well documented (Anderson and Bell, 2009; Bobb et al., 2014; Guo et al., 2012; O'Neill et al., 2005). However, the projection of heat wave-related mortality has not been well understood, in particular how the intensity of heat wave and adaptation to heat wave would impact health projections.

Conventionally, heat wave was modeled using a dummy variable indicating consecutive days with daily temperature exceeding a threshold, and the intensity of heat waves was modeled using the average temperature during heat wave periods (Anderson and Bell, 2011), using increasing threshold temperatures of heat waves (Anderson and Bell, 2009; Hajat et al., 2006), or using a dummy variable indicating if daily temperature exceeded a monthly percentile (D'Ippoliti et al., 2010). The epidemiological evidence has suggested that the effect of heat wave increases with its intensity. The intensity of heat waves could be considered implicitly in projections if one models temperature directly (Ballester et al., 2011; Schwartz et al., 2015). But it has not been commonly incorporated when heat wave is modeled using dummy variables.

Furthermore, heat-related mortality has declined over time (Bobb et al., 2014; Davis et al., 2003; Kyselý and Plavcová, 2011; Nordio et al., 2015; Petkova et al., 2014; Schifano et al., 2012). Several factors including development of early warning systems, improvement of health

---

* Corresponding author.
E-mail address: joel@hsph.harvard.edu (J.D. Schwartz).

https://doi.org/10.1016/j.envres.2017.11.049
Received 4 July 2017; Received in revised form 6 November 2017; Accepted 28 November 2017

care services, and change in infrastructure potentially attenuated heat-related health effects, which is referred to as adaptation. Many health projection studies assumed no future adaptation to heat waves and suggested that attributable mortality would increase substantially in the near future (Hayhoe et al., 2010; Huang et al., 2011; Jackson et al., 2010; Peng et al., 2011; Schwartz et al., 2015). A study that considered long-term adaptation used the temperature-mortality relationship from a warmer city to analogize the future temperature-mortality relationship in a warming city (Knowlton et al., 2007), which relies on an assumption that there is little spatial difference in the temperature-mortality relationship, adaptation, and socio-economic status (Huang et al., 2011). Some studies relied on other assumptions such as a complete adaptation for an increase in 1–4 °C (Ballester et al., 2011; Dessai, 2003; Gosling et al., 2009).

In addition, most projections to date for the U.S. restricted the study area to a few cities or used a small number of climate models (Gosling et al., 2009; Hayhoe et al., 2010; Huang et al., 2011; Jackson et al., 2010; Peng et al., 2011). Using data from different climate zones may help reveal potential spatial heterogeneity in heat wave-related mortality and projections.

The present study examined temperature-mortality time-series data in 209 U.S. cities during the period of 1962–1966 and 1973–2006 (Nordio et al., 2015). The cities had a population of 168 million and wide variations in geography and prevailing temperature (Supplemental material Fig. S1). For example, the 95th percentile of temperature across the cities ranged from 19 to 36 °C. We first improved the epidemiological modeling for the associations between heat waves and mortality by including intensity of heat waves and adaptation (which was estimated empirically using the time series for over 40 years), and then incorporated these estimates to project future mortality under different climate scenarios using a rich set of climate models.

2. Methods

2.1. Mortality and observed temperature data

Death certificates in 209 cities in the contiguous U.S. in 1962–2006 were obtained from National Center for Health Statistics (NCHS) and were aggregated into daily counts of all natural cause deaths in each of the cities. NCHS did not collect date of death from 1967 to 1972, and hence the death certificates in 1967–1972 were not used to construct the time-series data for daily count of mortality. There were 42 million deaths during 1962–1966 and 1973–2006 in 209 cities. Daily mean temperatures were obtained from Global Summary of the Day, National Climatic Data Center (NCDC, 2013). For each city, temperature was matched to the measurements from the nearest airport. When the temperature observations were missing, temperature observations from the nearest monitors within 60 km among other monitors were used. As a quality control, temperature data from a monitor were used if the monitors have at least 98% of the observations available during the period that the mortality data were collected (Nordio et al., 2015).

Heat waves in each of the cities were defined as at least two consecutive days with daily mean temperature exceeding the 95th percentile of the daily temperatures of that city (threshold temperature) in 1962–1966 and 1973–2006. The 95th percentile of daily temperature in each city was computed using daily mean temperatures for the entire period during 1962–1966 and 1973–2006. In other words, for a day to be a heat wave day, not only the daily temperature on that day has to exceed the threshold temperature of that city, but also the daily temperature on either or both of the day before and the day after that day has to exceed the threshold. Similar definitions of heat waves have been used in other studies (Anderson and Bell, 2009, 2011; Hajat et al., 2006). The excess heat factor (EHF) was used to characterize the intensity of heat exposure. For city c on a heat wave day i, EHF was defined as $\max(T_{c,i}-T_{95,c},\ 0) \times \max(T_{c,i}-(T_{c,i-1}+T_{c,i-2}+\ldots+T_{c,i-30})/30,\ 1)\ ^{\circ}\mathrm{C}^2$ where $T_{95,c}$ represents the 95th percentile of daily temperature of city c and $\max(T_{c,i}-T_{95,c},\ 0)$ represents how much the temperature of day i exceeds the threshold temperature (Nairn and Fawcett, 2015; Perkins et al., 2012). The difference between $T_{c,i}$ and the 30-day moving average takes into account the short-term physiological adaptation to heat exposure which partially explains the higher effect of heat in early summer than later summer (Garrett et al., 2012; Lee et al., 2014). The EHF was zero on non-heat wave days, since it was used to characterize the intensity of a heat wave day.

For regional analyses, we clustered the 209 cities into climate regions (Karl and Koss, 1984): northeast (n = 51), east north central (n = 21), central (n = 34), west north central (n = 2) northwest (n = 11), west (n = 18), southwest (n = 13), south (n = 21), and southeast (n = 38). Because there were only two cities in the west north central and both were near the border with east north central, these two cities were grouped into east north central.

2.2. Epidemiological modeling

In each city, over-dispersed Poisson regression models were fitted to the time series to estimate the association between heat waves days and daily mortality ($Y_{c,i}$) in each city c. Dummy variables for each year and for the day of the week (DOW_i) and a natural spline with six degrees of freedom for the day of the year were adjusted for in the model. The present study used an interaction term between heat wave and MST to model adaptation. EHF was used to describe the intensity of a heat wave. More formally, for city c on date i, the following four models were considered:

Model 1: ignoring adaptation and intensity,

$$\begin{aligned} log(E(Y_{c,i})) &= \beta_{c,0} + \beta_{c,1}HW_{c,i} + \sum_{j\neq Year_R} \beta_{c,j} I(Year_i = j) \\ &\quad + \sum_{k\neq DOW_R} \beta_{c,k} I(DOW_i = k) + ns(DOY_i; \boldsymbol{\beta_{ns}}, df = 6) \end{aligned} \tag{1}$$

Model 2: considering intensity but ignoring adaptation,

$$\begin{aligned} log(E(Y_{c,i})) &= \beta_{c,0} + \beta_{c,1}HW_{c,i} + \beta_{c,2}EHF_{c,i} + \sum_{j\neq Year_R} \beta_{c,j} I(Year_i = j) \\ &\quad + \sum_{k\neq DOW_R} \beta_{c,k} I(DOW_i = k) + ns(DOY_i; \boldsymbol{\beta_{ns}}, df = 6) \end{aligned} \tag{2}$$

Model 3: considering adaptation but ignoring intensity,

$$\begin{aligned} log(E(Y_{c,i})) &= \beta_{c,0} + \beta_{c,1}HW_{c,i} + HW_{c,i}s(MST_{c,i}; \boldsymbol{\beta_{c,HWMST}}) \\ &\quad + \sum_{j\neq Year_R} \beta_{c,j} I(Year_i = j) + \sum_{k\neq DOW_R} \beta_{c,k} I(DOW_i = k) \\ &\quad + ns(DOY_i; \boldsymbol{\beta_{ns}}, df = 6) \end{aligned} \tag{3}$$

Model 4: considering both intensity and adaptation,

$$\begin{aligned} log(E(Y_{c,i})) &= \beta_{c,0} + \beta_{c,1}HW_{c,i} + \beta_{c,2}EHF_{c,i} + HW_{c,i}s(MST_{c,i}; \boldsymbol{\beta_{c,HWMST}}) \\ &\quad + EHF_{c,i}s(MST_{c,i}; \boldsymbol{\beta_{c,EHFMST}}) + \sum_{j\neq Year_R} \beta_{c,j} I(Year_i = j) \\ &\quad + \sum_{k\neq DOW_R} \beta_{c,k} I(DOW_i = k) + ns(DOY_i; \boldsymbol{\beta_{ns}}, df = 6) \end{aligned} \tag{4}$$

where $HW_{c,i}$ is an indicator variable for heat wave days, $EHF_{c,i}$ is for the intensity, and $s(MST_{c,i}; \boldsymbol{\beta})$ is a piece-wise linear spline with a knot at the city-specific average of MST (yearly average of the daily temperature from June to August) for city c parameterized by $\boldsymbol{\beta}$. That is, we tested whether the effect of a heat wave on mortality in each city changed with MST, and whether that change was nonlinear with MST. In model 4, adaptation to heat waves was captured not only by the interaction between the heat wave indicator and MST but also by the interaction between its intensity and MST. $Year_i$, DOW_i, and DOY_i represent the year, day of the week, and day of the year of date i. $Year_R$ is the reference year when the dummy variables for each year