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Estimating and projecting the effect of cold waves on mortality in 209 US cities

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ABSTRACT

The frequency, duration, and intensity of cold waves are expected to decrease in the near future under the changing climate. However, there is a lack of understanding on future mortality related to cold waves. The present study conducted a large-scale national projection to estimate future mortality attributable to cold waves during 1960–2050 in 209 US cities. Cold waves were defined as two, three, or at least four consecutive days with daily temperature lower than the 5th percentile of temperatures in each city. The lingering period of a cold wave was defined as the non-cold wave days within seven days following that cold wave period. First, with 168 million residents in 209 US cities during 1962–2006, we fitted over-dispersed Poisson regressions to estimate the immediate and lingering effects of cold waves on mortality and tested if the associations were modified by the duration of cold waves, the intensity of cold waves, and mean winter temperature (MWT). Then we projected future mortality related to cold waves using 20 downscaled climate models. Here we show that the cold waves (both immediate and lingering) were associated with an increased but small risk of mortality. The associations varied substantially across climate regions. The risk increased with the duration and intensity of cold waves but decreased with MWT. The projected mortality related to cold waves would decrease from 1960 to 2050. Such a decrease, however, is small and may not be able to offset the potential increase in heat-related deaths if the adaptation to heat is not adequate.

1. Introduction

A number of studies have shown that exposure to temperature extremes is associated with an increased risk of mortality (Bobb et al., 2014b; Gasparrini et al., 2015; Kinney et al., 2015; Medina-Ramon and Schwartz, 2007; Nordio et al., 2015; Peng et al., 2011). Under the changing climate, the characteristics of extreme weather events have changed substantially during the past several decades, with an increase in the frequency, duration, and intensity of heat waves but a decrease in the frequency, duration, and intensity of cold waves (IPCC, 2013; Melillo et al., 2014; Perkins et al., 2012). Moreover, such a trend is very likely to continue in the future (IPCC, 2013), which would possibly be associated with an increase in heat wave-related mortality but a decrease in cold wave-related mortality in the future. Quantitatively estimating future heat- and cold-related mortality would add evidence to the debate over whether the changing climate would be harmful or beneficial to the public in the future. There have been several studies projecting future mortality related to extremely hot temperature or heat waves (Gosling et al., 2009; Hayhoe et al., 2010; Huang et al., 2011; Jackson et al., 2010; Peng et al., 2011). Nevertheless, what remains poorly understood is how many deaths would be attributable to cold waves under future climate scenarios.

A systematic assessment of cold-related mortality in the future requires high-quality epidemiologic estimates. First, mortality related to a cold wave would occur not only during the cold wave period (immediate effect) but also several days after the cold wave (lingering effect) (Anderson and Bell, 2009; Braga et al., 2001). To obtain the overall cold-related deaths, we need to estimate both the immediate and lingering effects. However, the epidemiologic estimates for the immediate effect of cold waves differed substantially across studies and there are fewer estimates for the lingering effects (Barnett et al., 2012; Gasparrini et al., 2015; Medina-Ramon and Schwartz, 2007; Rocklov et al., 2014; Ryti et al., 2016). Second, evidence on what factors modify the association between cold waves and mortality is limited. A change in the duration and intensity of cold waves may potentially modify the effect of cold waves as well as their lingering effect. In addition, there is evidence suggesting that an increase in mean summer temperature (MST) was associated with a decrease in heat-related deaths, referred to as adaptation (Nordio et al., 2015). But there is little evidence about if cold-related mortality is modified by mean winter temperature (MWT) and how people adapt to cold weather over time. A lack of

Abbreviations: MST, mean summer temperature; MWT, mean winter temperature; ECF, excess cold factor; EHF, excess heat factor; CMIP5, Coupled Model Intercomparison Project Phase 5; RR, relative risk; BM, baseline mortality.

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understanding of these aspects makes it difficult to project future mortality attributable to cold waves.

In the present work, we studied a population of 168 million residents in 209 US cities during 1962–2006. We estimated not only the percent change in daily mortality associated with the immediate and the lingering periods, but also the effect modifications of cold exposure by its duration, intensity, and MWT. With city-specific epidemiologic estimates, we further conducted large-scale projections of cold-related mortality for the 209 US cities during 1960–2050 using 20 climate models and four future emission scenarios.

2. Methods

2.1. Mortality, study domain, and observed temperature data

We obtained death certificates from the National Center for Health Statistics (NCHS) over the periods of 1962–1966 and 1973–2006. The date of death was not collected by NCHS during 1967–1972 and was excluded from the study. 209 cities in the contiguous US could be matched with daily temperature measurements from monitors with <2% missing values (Nordio et al., 2015). Then we aggregated the death certificates into the daily counts of all natural cause deaths.

The 209 cities were grouped into nine climate regions (Karl and Koss, 1984). There were 51 cities in the northeast, 21 in the east north central, 34 in the central, 2 in the west north central, 11 in the northwest, 18 in the west, 13 in the west, 21 in the south, and 38 in the southeast. The only two cities in the west north central region were located near the border between the west north central and the east north central. Hence, we grouped these two cities with the east north central.

Observed daily temperatures were used to identify cold wave days in each city. Cold waves could be defined in a similar way to heat waves. There are potentially many ways to define cold waves in the literature (Anderson and Bell, 2009; Anderson and Bell, 2011; Bobb et al., 2014a; Diaz et al., 2015; Tong et al., 2014; Xu et al., 2016). We made use of one of the most widely used approach combining a temperature test and a duration test. Cold wave days were defined as consecutive days of daily mean temperature below the 5th percentile (threshold temperature) of all daily mean temperatures during the period of study in that city. We considered three types of cold wave days with different durations: daily temperature below the threshold for two, three, or at least four consecutive days. As a sensitivity analysis, we also used the 3rd percentile of temperatures as the threshold and examined the difference in mortality related to cold waves with different lengths. We defined the lingering period of a cold wave period as the non-cold wave days within seven days following that cold wave period.

We defined an excess cold factor (ECF), an analogue to the excess heat factor (EHF), to characterize the intensity of a cold wave day

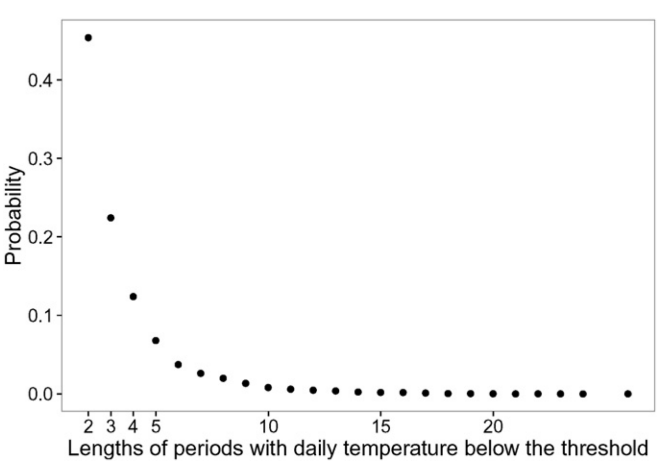

Fig. 1. The distribution of the lengths of cold wave periods.

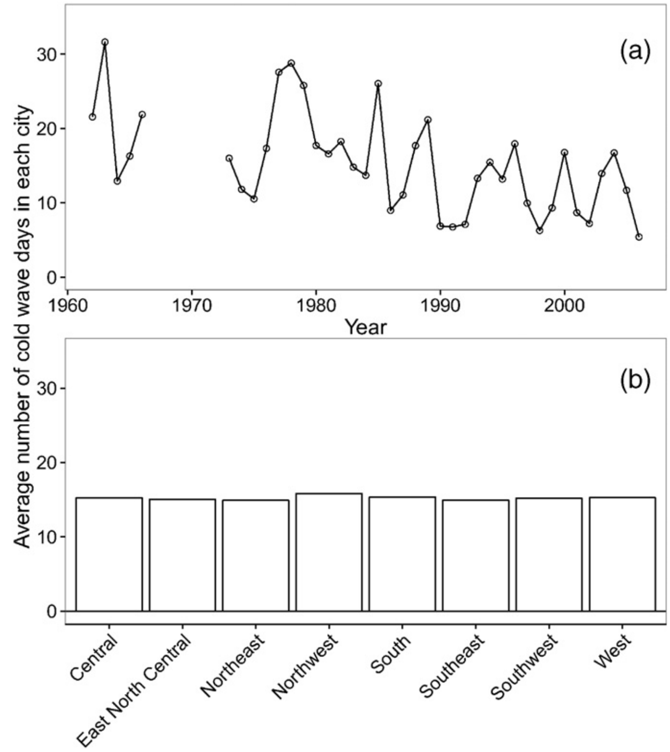

Fig. 2. Average number of cold wave days in each city by (a) year and (b) climate region.

(Nairn and Fawcett, 2015; Perkins et al., 2012). The basic idea of ECF is to quantify the intensity of a cold wave considering how much colder a day was compared to the minimum criteria for being a cold wave day and how much colder the day was compared to the 30 day trailing average which captures the amount of short-term adaptation to cold that may have occurred prior to the cold wave (Barnett et al., 2012). Formally, we defined the ECF of cold wave day i in city c as $\min(T_{c,i} - T_{5,c}, 0) \times \min(T_{c,i} - (T_{c,i-1} + T_{c,i-2} + \dots + T_{c,i-30})/30, -1)°C^2$, where $T_{5,c}$ was the 5th percentile of daily mean temperature in city c. $\min(T_{c,i} - T_{5,c}, 0)$ represents how much the daily temperature was below the 5th percentile, and $\min(T_{c,i} - (T_{c,i-1} + T_{c,i-2} + \dots + T_{c,i-30})/30, -1\ °C)$ shows the deviation of the temperature on day i from the monthly average. On non-cold wave days, the ECF was set at zero.

Statistical significance was defined as p values <0.05. All statistical analyses were conducted in R 3.2.2.

2.2. Epidemiologic modeling

The relative risk (RR) in a city c on a cold wave day compared to a non-cold wave day was estimated using an over-dispersed Poisson regression. We fitted the model for each of the cold wave definitions and controlled for a long-term time trend, seasonality, and day of the week. Formally, for city c on day i in year j, we assumed

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

where $Y_{c,i}$ is the number of daily deaths, $CW_{c,i}$ is an indicator variable for a cold wave day, $I(year_i = j)$ is a dummy variable for each year to control for time trend with a referent year $Year_R$, $I(DOW_i = k)$ is dummy variables for day of the week with a reference DOW_R, and $ns(DOY_i; \beta_{ns}, df = 6)$ is a natural spline for day of the year with six degrees of freedom to capture seasonality. The adjusted RR of mortality on cold wave days is $\exp(\beta_{c,1})$ in city c. When estimating the lingering