Published in final edited form as:

Environ Int. 2016 September ; 94: 141–149. doi:10.1016/j.envint.2016.05.008.

Estimating and Projecting the Effect of Cold Waves on Mortality in 209 US Cities

Yan Wang¹, Liuhua Shi¹, Antonella Zanobetti¹, and Joel D. Schwartz¹

¹Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA

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 also small and may not be able to offset the potential increase in heat-related deaths.

Keywords

cold wave; mortality; projections; climate change

1. Introduction

A number of studies have shown that exposure to temperature extremes is associated with an increased risk of mortality (Bobb and others 2014b; Gasparrini and others 2015; Kinney and others 2015; Medina-Ramon and Schwartz 2007; Nordio and others 2015; Peng and others

Correspondence to Yan Wang, Department of Environmental Health, Harvard T.H. Chan School of Public Health, 401 Park Drive, PO Box 15677, Boston, MA, USA 02215; yaw719@mail.harvard.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Competing Financial Interests: None declared.

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 and others 2014; Perkins and others 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 and others 2009; Hayhoe and others 2010; Huang and others 2011; Jackson and others 2010; Peng and others 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 and others 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 and others 2012; Gasparrini and others 2015; Medina-Ramon and Schwartz 2007; Rocklov and others 2014; Rytö and others 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 and others 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 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 less than 2% missing

values (Nordio and others 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 and others 2014a; Diaz and others 2015; Tong and others 2014; Xu and others 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 kinds 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 3rd percentile of temperatures as the threshold and examined the difference in mortality related to cold waves with different lengths. We also 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 (Nairn and Fawcett 2015; Perkins and others 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 and others 2012). Formally, we defined the ECF of cold wave day i in city c as $\min(T_{c,i} - T_{5,c}, 0) \times \min(T_{c,i} - (T_{c,i-1} + T_{c,i-2} + \dots + T_{c,i-30})/30, -1) \text{ } ^\circ\text{C}^2$, 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 $\min(T_{c,i} - (T_{c,i-1} + T_{c,i-2} + \dots + T_{c,i-30})/30, -1 \text{ } ^\circ\text{C})$ 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 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

$$\log(E(Y_{c,i})) = \beta_{c,0} + \beta_{c,1}CW_{c,i} + \sum_{j \neq \text{Year}_R} \beta_{c,j}I(\text{Year}_i=j) + \sum_{k \neq \text{DOW}_R} \beta_{c,k}I(\text{DOW}_i=k) + ns(\text{DOY}_i; \beta_{ns}, df=6)$$

(1)

where $Y_{c,i}$ is the number of daily deaths, $CW_{c,i}$ is an indicator variable for a cold wave day, $I(\text{year}_i = j)$ is a dummy variable for each year to control for time trend with a referent year Year_R , $I(\text{DOW}_i = k)$ is dummy variables for day of the week with a reference DOW_R , and $ns(\text{DOY}_i; \beta_{ns}, df=6)$ 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 effect of cold waves, we also used equation (1) but replaced the cold wave indicator with the indicator for the lingering days which are the non-cold wave days within seven days of a cold wave. For each of the cold wave definitions, we meta-analyzed the city-specific coefficients to obtain the national and regional effects using random-effect models. We conducted several sensitivity analyses to assess the robustness of the epidemiologic estimates. First, instead of controlling for a universal seasonality using one natural spline, we controlled for separate seasonal trends (the natural spline for day of the week) for each decade. Second, we replaced the natural spline with six degrees of freedom with a natural spline with eight degrees of freedom. Third, we obtained city-specific average summer mortality and regressed it against a linear variable of year. We added to the model an interaction term between the mortality residuals in the previous summer and cold waves in addition to an interaction between cold waves and the spline of MWT. This could test the hypothesis that whether a high mortality rate in the summer would decrease the number of individuals at risk and thus alter the cold wave-related mortality in the next winter.

We tested if the immediate and lingering effects of cold waves were modified by MWT for each year in each city. The MWT was modeled using a piece-wise linear spline with a knot at the average of the MWT in each city. We also tested if the effect of cold wave was modified by the intensity, ECF.

2.3. Risk assessment

The risk assessment aimed to project the mortality related to cold waves during 1960–2050 using the city-specific epidemiologic estimates and temperature projections from climate models. Temperature projections were obtained from 20 downscaled (0.125°) Bias-Correction Constructed Analog Version 2 (BCCAv2) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model dataset. The CMIP5 simulations use a new set of emission scenarios, Representative Concentration Pathways (RCPs), based on radiative forcing trajectories. One historical and four future RCPs (2.6, 4.5, 6.0, and 8.5) were used. The city-specific daily temperatures were obtained by matching each city to its nearest grid cell in CMIP5. We defined cold wave days during 1960–2050 using the same definitions for each city we used in our epidemiologic analyses. We accounted for the change in RR with

MWT in risk assessment by using the epidemiologic models that included an interaction of MWT with cold waves or an interaction of MWT with lingering periods.

We estimated an average baseline mortality for city c on non-cold wave days ($BM_{c, \text{non-cw}}$) and on non-lingering days ($BM_{c, \text{non-linger}}$) using the epidemiologic models for each cold wave definition. The interpretation of the projected mortality represents the mortality attributable to cold waves which are two to at least four consecutive days of days with daily temperatures below the threshold temperature in that city. Then the attributable mortality for the immediate and lingering effects of cold wave days was the additional mortality had that day been not a cold wave day or a lingering day. The mortality attributable to the immediate effect of cold waves was hence estimated by $BM_{c, \text{non-cw}} (RR_{c, \text{cold wave}} - 1)$; and the daily mortality attributable to lingering periods was $BM_{c, \text{non-non-linger}} (RR_{c, \text{lingering}} - 1)$. To focus on the change in future cold wave events and RR, we assumed no change in demography or baseline mortality rate. This ensures that the change in projected mortality would be more interpretable and not be intertwined with changes in other factors.

3. Results

On average, there were 4.4 cold wave periods in each city each year. Figure 1 shows the distribution of the length of cold wave periods. Two-day cold wave periods represent 45% of all cold waves, three-day cold wave periods represent 22%, and four-day cold wave periods represent 12%. Cold waves with longer durations represented less than 10% each. The number of cold wave days decreased from the 1960s to the 2000s (Figure 2 panel a) and distributed evenly across climate regions (Figure 2 panel b).

The percent change in mortality associated with the immediate effect of cold waves increased with the duration of cold waves nationally (Figure 3 panel a). The immediate effect of two-day cold waves on mortality was close to the null, whereas the three-day or at least four-day cold waves were significantly associated with an increased risk of mortality. Cold waves had a smaller effect when MWT was at the 80th percentile compared to the 20th percentile (Figure 3 panel b), suggesting there was an interaction between cold waves and MWT. We obtained a consistent trend if we used the 3rd percentile as the temperature cutoff (Figure 4). The result is also robust to further adjustment of seasonality using separate natural splines for each decade (Figure 5) or changing the degrees of freedom of the spline for seasonality from six to eight (Figure 6). The effect of cold waves was also significantly modified by their intensities (Figure 7). For a three-day or longer cold wave, an increase in ECF was associated with an additional increase in mortality. Cold waves of all durations had lingering effects. Longer cold waves were associated with a slightly higher lingering effect (Figure 8 panel a). There was also an interaction between the lingering periods and MWT: larger lingering effects were found in years with lower MWT (Figure 8 panel b). After adding interaction between cold waves and a spline of MWT, the interaction between mortality in the previous summer and cold waves in the next winter was not statistically significant.

In regional analyses, two-day cold waves were not significantly associated with a change in mortality in any of the eight regions (Figure 9 panel a). Three-day cold waves were

associated with a significantly increased risk of death in the northeast and the southeast (Figure 9 panel b). Cold waves with a duration of at least four days were associated with a statistically significantly increased risk of death in the northeast, south, central, and southeast (Figure 9 panel c). By comparison, the lingering effects were statistically significant for almost all regions and durations of cold waves (Figure 10). The lingering effects in most regions were larger than the immediate effect of cold waves.

The projected mortality during 1960–2050 associated with the immediate and lingering effects of cold waves are presented in Figure 11. Under the four future RCP scenarios, the mortality attributable to the effect of cold waves, their lingering effect, and the overall effect are expected to decrease over time. The mortality attributable to the lingering periods are higher than the immediate mortality. There were small differences between low and high emission scenarios by 2050. In the regional projections, decreasing trends of cold-related deaths were found in the northeast, central, east north central, south, and southeast (Figure 12). The west showed a decreasing trend in mortality after 2000.

In the sensitivity analysis, we compared the projected mortality using historically observed temperature and climate models. The climate models overestimated the attributable mortality (Figure 13).

4. Discussions

With a population of 168 million people in 209 US cities, we found that the immediate and lingering effects of cold waves were associated with an increase in mortality among the US urban population, and longer cold waves had higher impact. The immediate effect of cold waves is, however, small. The mortality related to the lingering periods of cold waves was much larger. Projections using a rich set of climate models suggested that future mortality associated with the immediate and lingering effect of cold waves would decrease over time. The decrease, however, was small.

Although there have been some studies suggesting a warming climate would bring limited benefit to reduce mortality in winters (Kinney and others 2015; Staddon and others 2014), very few studies provided a quantitative assessment of future cold-related mortality or large-scale mortality projections. In the present study, we show that the decrease in yearly mortality by 2050 associated with the immediate effects was only around 500 across 209 cities. The decrease in yearly mortality due to the lingering effects within seven days of cold waves was only around 1000. Although a warming climate would potentially decrease the number of extreme cold events, the health benefit would not be substantial.

The projected mortality when the MWT was ignored was close to the mortality when the MWT was considered. This suggests that the decrease in mortality would mostly be contributed by the decrease in the number of cold waves instead of the decrease in RR as MWT increased. Consistent with the larger lingering effect, we found more attributable mortality would be associated with the lingering periods in the future than with the cold wave periods. This is also consistent with a previous study which showed that more cold-related mortality occurred on moderately cold periods than the extremely cold days

(Gasparrini and others 2015). One caveat is that we chose seven days as a representative duration of lingering period. The larger attributable mortality to the lingering effect is a combination of the larger relative risk on lingering days and the larger number of lingering days. Although the lingering effect may exceed seven days, we may not be able to further increase in the length of lingering period in the present study. There were 4.4 cold wave periods each year in each city corresponding to approximately a month of lingering days. We could not distinguish lingering effects from seasonality if we further increase the number of days for each lingering period. This was also suggested by the results of Kinney et al. (2015) (Kinney and others 2015). Moreover, some studies suggested that the lingering effect of cold exposure is the largest within the ten days using distributed lag models (Analitis and others 2008; Armstrong 2006). In our study, the total of a typical cold wave which lasted for two to four days and a lingering period of seven days was nine to eleven days, which is comparable to the period with the largest cold-related effects. Hence, we think that seven days is a reasonable representative of lingering period. After adding the interaction between MWT and cold waves, there was not statistically significant interaction between the mortality anomaly from the previous summer and cold waves.

The estimates for the cold wave effect in existing literatures are inconsistent across studies. Our results suggested that the percent increase in mortality on cold wave days ranged from approximately the null (two-day) to 2.1%. By comparison, a previous study in the US reported a 1.59% increase in mortality during cold waves (Medina-Ramon and Schwartz 2007). A meta-analysis including studies from Netherlands, Yatsusk, and China reported a much larger, 10%, increase in mortality (Ryti and others 2016). Such a difference would be explained by the climate, adaptation, and socioeconomic status of each country which future studies could look into.

Heat waves were associated with a larger increase in mortality than cold waves. For example, a study of 50 US cities reported a 5.9% increase in mortality on heat wave days (Medina-Ramon and Schwartz 2007). Another study in Chicago reported a 7.8% increase (Peng and others 2011). A study in 107 US communities reported a 3.0% increase (Anderson and Bell 2009). Again, compared with the small health benefit from a decrease in the number of cold wave events, future mortality associated with heat waves would be a bigger concern if there is no proper adaptation to heat or adaptation has already reached its limit.

We found that the immediate effect of cold waves increased with its duration and that the lingering effects of cold waves were larger than the cold waves themselves. The percent change in mortality for a two-day cold wave was close to the null whereas the mortality increased by 1.7% during the lingering periods. A long cold wave had a larger lingering effect compared to a short cold wave. The difference, however, is small. That is, a short cold wave still has large lingering effect. As cold waves become longer, their effects get closer to the lingering effects. One possible reason is that a cold wave day in the later phase of a long cold wave period posed a combination of the immediate effect of cold wave and the lingering effect of the cold wave days in early phase. This result may be explained by the longer-lasting and delayed effect of cold waves (Anderson and Bell 2009; Braga and others 2001). The projected mortality showed a similar pattern: the attributable deaths to the

lingering periods of cold waves were higher than the deaths related to the immediate effect of cold waves.

A cold wave also had higher effect if that cold wave was more intense. The intensity was measured by the ECF in this study. The ECF takes into account not only how much the daily temperature exceeded the threshold temperature. It also combined information about how much the daily temperature exceeded the moving average in the previous 30 days, which is related to short-term acclimatization including behavioral changes and physical adaptation (Anderson and Bell 2009). We also observed the interactions of MWT with cold wave periods. Warm winters had a smaller effect of cold waves. By comparison, heat waves had a lower effect on mortality as MST increased (Nordio and others 2015). In addition, the lingering effect was also modified by MWT. A cold wave in warmer winters had not only a smaller effect itself but also a smaller lingering effect. So such a pattern is different from how people get adapted to heat exposure over time. In contrast, a previous study for 99 US cities showed a statistically insignificant change in mortality on cold wave days and suggested that more intense or longer cold waves were not more dangerous (Barnett and others 2012). One possible explanation for the discrepancy between two studies is that we used more cities and we used more than 40 years of data to estimate the associations.

After grouping the 209 cities into climate regions, we found a substantial spatial heterogeneity for the cold-related effect and projected mortality across climate regions. The effect of cold waves was mostly observed in the northeast, south, central, and southeast which are generally the eastern part of the country. The lingering effect, by comparison, was observed in each of the climate regions. The highest effect of cold wave and the highest lingering effect were found in the southeast, whereas they were generally weak in the southwest. So the spatial contrast shows a different pattern from the within-city temporal trend where warm winters have a smaller effect. The spatial pattern may be explained by a combination of the severity of cold waves and adaptation. However, the present study did not measure each of the adaptation strategies and it would be difficult to determine which strategy would be the most relevant. The projected mortality showed that the northeast, central, east north central, south, southeast, and west would benefit from a decrease in cold wave occurrences. The northwest and southwest had little changes. The implication is that future policies regarding reducing cold-related deaths need to be regional.

We acknowledge that the present study has limitations. First, we have observed that the climate models may overestimate the attributable mortality under historical scenario of the climate model (Figure 8), which might be a result from the biasedness of the climate models. Similar bias may occur under all four RCP scenarios. Although recent studies have found that the downscaled climate models well simulate the observed means in each grid cells, it is difficult for the current models to simulate the extremes (Guentchev and others 2016; Keellings 2016). For example, Guentchev et al. (2016) studied the performance of the BCCA downscaled climate models in Washington D.C. area and found that there is an underestimation of the number of days with extremely high daily maximum temperature (> 35 degree C) whereas the number of days with daily maximum temperature greater than 30 degree C was less biased in summer seasons (Guentchev and others 2016). Keellings (2016) studied the southeastern US and found that there is an underestimation of the frequency of

days with daily maximum temperature greater than 30 degree C (Keellings 2016). Future research using less biased downscaled climate models that are able to better capture the occurrence of extreme temperatures would help address this issue. Although the absolute values of mortality may also be biased as a result, the temporal trend of mortality would be useful information about how mortality would change over time in the future. Second, the mortality data were only collected for the 209 cities and rural residents were underrepresented. Future studies using a general population and a spatially-resolved temperature dataset would make the epidemiologic estimate more generalizable and provide information for larger-scale projections. Third, the projections isolated the attention to future mortality related to changes in cold waves and cold seasons and ignored other factors such as population and age structure. Hence, the absolute value of the projected mortality is not an exact estimate for future cold wave-related mortality. The projections reflected what would happen in the future had the climate changed, holding other factors constant. This issue could be addressed in future studies by taking other factors such as demographic changes into account.

5. Conclusions

We estimated the cold-related mortality using a population of 168 million residents in 209 US cities and projected the mortality in 1960–2050. Although cold waves and their lingering periods were associated with increased risk of mortality, the effect estimates and the decrease in projected mortality over time were generally small. The effect of cold waves and the lingering effect were modified by the intensity of cold waves and MWT. We have also observed a substantial spatial heterogeneity in the relative risk and projected mortality. These findings will provide information for better-coordinated responses to the impact of climate change on public health.

Acknowledgments

This publication was made possible by USEPA grant RD-83479801. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the USEPA. Further, USEPA does not endorse the purchase of any commercial products or services mentioned in the publication. It was also supported by NIH grant R21ES024012.

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

References

- Analitis A, Katsouyanni K, Biggeri A, Baccini M, Forsberg B, Bisanti L, Kirchmayer U, Ballester F, Cadum E, Goodman PG, Hojs A, Sunyer J, Tiittanen P, Michelozzi P. Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. *American journal of epidemiology*. 2008; 168:1397–1408. [PubMed: 18952849]
- Anderson BG, Bell ML. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology (Cambridge, Mass)*. 2009; 20:205–213.
- Anderson GB, Bell ML. Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental health perspectives*. 2011; 119:210–218. [PubMed: 21084239]
- Armstrong B. Models for the relationship between ambient temperature and daily mortality. *Epidemiology (Cambridge, Mass)*. 2006; 17:624–631.
- Barnett AG, Hajat S, Gasparrini A, Rocklov J. Cold and heat waves in the United States. *Environmental research*. 2012; 112:218–224. [PubMed: 22226140]
- Bobb JF, Obermeyer Z, Wang Y, Dominici F. Cause-specific risk of hospital admission related to extreme heat in older adults. *Jama*. 2014a; 312:2659–2667. [PubMed: 25536257]
- Bobb JF, Peng RD, Bell ML, Dominici F. Heat-related mortality and adaptation to heat in the United States. *Environmental health perspectives*. 2014b; 122:811–816. [PubMed: 24780880]
- Braga AL, Zanobetti A, Schwartz J. The time course of weather-related deaths. *Epidemiology (Cambridge, Mass)*. 2001; 12:662–667.
- Diaz J, Carmona R, Miron IJ, Ortiz C, Leon I, Linares C. Geographical variation in relative risks associated with heat: Update of Spain's Heat Wave Prevention Plan. *Environment international*. 2015; 85:273–283. [PubMed: 26433629]
- Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, Tobias A, Tong S, Rocklov J, Forsberg B, Leone M, De Sario M, Bell ML, Guo YL, Wu CF, Kan H, Yi SM, de Sousa Zanotti Stagliorio Coelho M, Saldiva PH, Honda Y, Kim H, Armstrong B. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet (London, England)*. 2015; 386:369–375.
- Gosling S, McGregor G, Lowe J. Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. *International journal of biometeorology*. 2009; 53:31–51. [PubMed: 19052780]
- Guentchev GS, Rood RB, Ammann CM, Barsugli JJ, Ebi K, Berrocal V, O'Neill MS, Gronlund CJ, Vigh JL, Koziol B, Cinquini L. Evaluating the Appropriateness of Downscaled Climate Information for Projecting Risks of Salmonella. *International journal of environmental research and public health*. 2016; 13
- Hayhoe K, Sheridan S, Kalkstein L, Greene S. Climate change, heat waves, and mortality projections for Chicago. *Journal of Great Lakes Research*. 2010; 36(Supplement 2):65–73.
- Huang C, Barnett AG, Wang X, Vaneckova P, Fitzgerald G, Tong S. Projecting future heat-related mortality under climate change scenarios: a systematic review. *Environmental health perspectives*. 2011; 119:1681–1690. [PubMed: 21816703]
- IPCC. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013. *Climate Change 2013: The Physical Science Basis*.
- Jackson JE, Yost M, Karr C, Fitzpatrick C, Lamb B, Chung S, Chen J, Avise J, Rosenblatt R, Fenske R. Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climatic Change*. 2010; 102:159–186.
- Karl T, Koss WJ. Regional and national monthly, seasonal, and annual temperature weighted by area, 1895–1983: National Climatic Data Center. 1984
- Keellings D. Evaluation of downscaled CMIP5 model skill in simulating daily maximum temperature over the southeastern United States. *International Journal of Climatology*. 2016 n/a-n/a.

- Kinney PL, Schwartz J, Pascal M, Petkova E, Tertre AL, Medina S, Vautard R. Winter Season Mortality: Will Climate Warming Bring Benefits? *Environmental research letters : ERL* [Web site]. 2015; 10:064016.
- Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occupational and environmental medicine*. 2007; 64:827–833. [PubMed: 17600037]
- Melillo JM, Richmond TTC, Yohe GW. Climate change impacts in the United States. Third National Climate Assessment. 2014
- Nairn JR, Fawcett RJ. The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. *International journal of environmental research and public health*. 2015; 12:227–253. [PubMed: 25546282]
- Nordio F, Zanobetti A, Colicino E, Kloog I, Schwartz J. Changing patterns of the temperature-mortality association by time and location in the US, and implications for climate change. *Environment international*. 2015; 81:80–86. [PubMed: 25965185]
- Peng RD, Bobb JF, Tebaldi C, McDaniel L, Bell ML, Dominici F. Toward a quantitative estimate of future heat wave mortality under global climate change. *Environmental health perspectives*. 2011; 119:701–706. [PubMed: 21193384]
- Perkins SE, Alexander LV, Nairn JR. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*. 2012; 39 n/a-n/a.
- Rocklov J, Forsberg B, Ebi K, Bellander T. Susceptibility to mortality related to temperature and heat and cold wave duration in the population of Stockholm County, Sweden. *Global health action*. 2014; 7:22737. [PubMed: 24647126]
- Ryti NR, Guo Y, Jaakkola JJ. Global Association of Cold Spells and Adverse Health Effects: A Systematic Review and Meta-Analysis. *Environmental health perspectives*. 2016; 124:12–22. [PubMed: 25978526]
- Staddon PL, Montgomery HE, Depledge MH. Climate warming will not decrease winter mortality. *Nature Clim Change*. 2014; 4:190–194.
- Tong S, Wang XY, Yu W, Chen D, Wang X. The impact of heatwaves on mortality in Australia: a multicity study. *BMJ open*. 2014; 4:e003579.
- Xu Z, FitzGerald G, Guo Y, Jalaludin B, Tong S. Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environment international*. 2016; 89–90:193–203.

Highlights

- We provided large-scale quantitative projections on future cold-related mortality in the US.
- Cold waves, both its immediate and lingering effects, are related to an increased risk of mortality and were modified by the duration and intensity of cold waves and mean winter temperature.
- Future mortality related to cold waves is expected to decrease, but the reductions are small and may not be able to offset the potential increase in heat-related deaths.
- The substantial spatial heterogeneity in the excess risk related to cold waves and the projected mortality suggested that the public health policies to reduce cold-related mortality need to be regional.

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

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

Figure 3. Percent change in mortality during two-day, three-day, and at least four-day cold waves. (a) Overall change (b) given MWT at the 20th or the 80th percentile.

Figure 4. Using the 3rd percentile temperature in each city to define cold waves. Percent change in mortality during two-day, three-day, and at least four-day cold waves. (a) Overall change (b) given MWT at the 20th or the 80th percentile.

Figure 5.
Same as figure 3 except controlling for separate seasonality for each decade.

Figure 6.

Same as figure 3 except controlling for seasonality using a natural spline with eight degrees of freedom.

Figure 7. Effect modifications of cold waves by ECF. The grey bars represent the percent change in mortality on a cold wave day at the threshold temperature. The white bars represent the additional change in mortality on cold wave days per interquartile range increase in ECF.

Figure 8. Percent change in mortality during the lingering periods of two-day, three-day, and at least four-day cold waves. (a) Overall change (b) given MWT at the 20th or the 80th percentile.

Figure 9.

In each of the climate regions, percent change in mortality during (a) two-day, (b) three-day, and (c) at least four-day cold waves.

Figure 10.

In each of the climate regions, percent change in mortality during the lingering periods of (a) two-day, (b) three-day, and (c) at least four-day cold waves.

Figure 11.

Projected mortality in 209 US cities during 1960–2050 under historical, RCP 2.6, 4.5, 6.0, and 8.5. Panels (a) (b) (c) represent the projected mortality during cold waves, lingering periods of cold waves, and overall cold-related mortality. Panels labeled 1 did not consider an interaction between MWT and cold waves or lingering periods, whereas panels labeled 2 included such a term.

Figure 12.

Projected cold-related mortality (cold waves + lingering) in each of the climate regions during 1960–2050 under historical, RCP 2.6, 4.5, 6.0, and 8.5 scenarios.

Figure 13.
Projected cold-related mortality (cold waves + lingering) using historical temperature predictions from climate models (red) and using observed temperature (blue).