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Cold and heat waves in the United States

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Abstract

Extreme cold and heat waves, characterised by a number of cold or hot days in succession, place a strain on people's cardiovascular and respiratory systems. The increase in deaths due to these waves may be greater than that predicted by extreme temperatures alone.

We examined cold and heat waves in 99 US cities for 14 years (1987–2000) and investigated how the risk of death depended on the temperature threshold used to define a wave, and a wave's timing, duration and intensity. We defined cold and heat waves using temperatures above and below cold and heat thresholds for two or more days. We tried five cold thresholds using the first to fifth percentiles of temperature, and five heat thresholds using the ninety-fifth to ninety-ninth percentiles. The extra wave effects were estimated using a two-stage model to ensure that their effects were estimated after removing the general effects of temperature.

The increases in deaths associated with cold waves were generally small and not statistically significant, and there was even evidence of a decreased risk during the coldest waves. Heat waves generally increased the risk of death, particularly for the hottest heat threshold. Cold waves of a colder intensity or longer duration were not more dangerous. Cold waves earlier in the cool season were more dangerous, as were heat waves earlier in the warm season.

In general there was no increased risk of death during cold waves above the known increased risk associated with cold temperatures. Cold or heat waves earlier in the cool or warm season may be more dangerous because of a build up in the susceptible pool or a lack of preparedness for cold or hot temperatures.

Keywords: climate, mortality, weather, temperature, heat waves

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Ethical approval

The study used publicly available de-identified data and so no ethics applications were made.

1. Introduction

Recent record low temperatures in Northern Europe and the United States (US) highlight the potential health and societal impacts of extreme winter weather. Although there were dramatic media reports of deaths from hypothermia across much of Europe (BBC News, 2009), cold weather also contributes to a wider range of impacts on public health, including deaths from respiratory and cardiovascular diseases.

The association between ambient temperature and mortality has been demonstrated in many parts of the world (The Eurowinter Group, 1997; Barnett et al., 2005; Gosling et al., 2009). The relationship is usually U-shaped, with increased risks for cold and hot temperatures. When hot or cold temperature extremes last for a number of days there may be additional risks because of the extra pressures on the body's heating and cooling systems, and the extra demand on health services which can become over-stretched when many people fall ill. Sustained extremes of temperature over a number of consecutive days can be described as heat or cold waves.

Due to global climate change there is much concern about the health impact of heat waves. Thus, the most recent studies have investigated the additional effects of current and future heat waves (D'Ippoliti et al., 2010; Rocklöv et al., 2011; Anderson and Bell, 2011; Gasparrini and Armstrong, 2011; Peng et al., 2011). There has been less work on cold waves, despite cold weather continuing to be a significant health problem (Rocklöv et al., 2011), and the concern that climate change will cause an increase in the intensity of winter storms (U.S. Climate Change Science Program, 2008). A previous paper reported significant excess all-cause mortality during cold spells in Holland (Huynen et al., 2001). Other studies have also reported increased mortality risks during cold spells. However, the underlying temperature response may not have been adequately controlled for, meaning the observed increases are not necessarily due to wave effects (Medina-Ramón and Schwartz, 2007; Revich and Shaposhnikov, 2008; Kysely et al., 2009; Montero et al., 2010; Revich and Shaposhnikov, 2010). Also, unlike with heat wave research, where it is known that characteristics such as heat wave duration, intensity and timing during season are associated with the mortality response, little is currently known about which characteristics of cold waves, if any, are most relevant to public health.

The aim of this paper is to estimate if there is an extra effect of cold and heat waves on mortality after adjusting for temperature and season. In other words, are the impacts of cold or hot days heightened if they occur in sequence? We were also interested in whether cold waves earlier in the cool season caused greater health effects than those later in the season, as may be the case with heat waves (D'Ippoliti et al., 2010; Rocklöv et al., 2011; Anderson and Bell, 2011). We also examined whether longer or more intense cold waves had a greater impact on mortality.

2. Materials and methods

We used the US National Morbidity and Mortality Air Pollution Study (NMMAPS) data from 1987–2000 (14 years) covering 108 cities (Samet et al., 2000) (downloaded from `http://www.ihapss.jhsph.edu/data/data.htm`, November 2010). To reduce the influence of missing data, we excluded cities with more than 0.5% missing data for air or dew point temperature, which left 99 cities (Supplementary Figure 1).

We used a two-stage analysis. First we fitted a time series model in every city with parameters for day of the week, holidays, influenza deaths, season and temperature. Then we fitted a Bayesian model to estimate any extra effects from cold and heat waves, and examine whether these effects depended on the waves timing, duration or intensity. We used this two stage procedure to ensure that the wave effects were estimated after removing the general effects of temperature and season.

We used the following Poisson regression model in each city,

$$d_t \sim \text{Poisson}(\mu_t), \qquad t = 1, \dots, T,$$

$$
\begin{aligned}
\log(\mu_t) &= \alpha_0 + \alpha_1 \text{holiday}_t + \alpha_2 \text{influenza}_t + \boldsymbol{\gamma}\text{DOW}_t + \text{ns}(t, \text{dfy} \times 14) + \\
&\quad \text{ns}(\text{dew point temperature}_t, \text{dfd}, \text{dfld}) + \\
&\quad \text{ns}(\text{mean temperature}_t, \text{dft}, \text{dflt}), \qquad (1)
\end{aligned}
$$

where d_t is the number of deaths on day t (excluding accidental and influenza deaths), holiday is a federal holiday (yes/no), influenza is the daily number of influenza deaths, DOW is day of the week, and T is the total number of days ($T = 5, 114$). We used a natural spline with dfy signifying the degrees of freedom per year to control for trends and season, which we varied from four to six.

The term ns(,dft,dflt) is a two-dimensional natural spline with dft signifying the degrees of freedom for temperature and dflt signifying the degrees of freedom for lagged temperature (Gasparrini et al., 2010). The spline captures the delayed effects of temperature, and we assumed a maximum delay of 21 days. The degrees of freedom control the flexibility of the association between temperature and the risk of death, with larger values allowing a more flexible association. For dew point temperature we used four degrees of freedom for both the temperature and lag. For mean temperature we tried one to six degrees of freedom to capture a range of flexibilities, and also fitted a model without mean temperature (which we label zero degrees of freedom). We consistently used five degrees of freedom for the lag of mean temperature, which allowed a reasonably flexible association for delayed effects.

2.1. Cold and heat waves

We defined a cold wave as a temperature below a cold threshold for two or more consecutive days. We tried a range of cold thresholds by using the first to fifth percentiles of temperature in each city. This is a cold extreme relative the local climate, an approach which has been shown to give more homogeneous effects in the US (Anderson and Bell, 2010). A heat wave was similarly defined as a temperature above a heat threshold for two or more consecutive days, with heat thresholds from the ninety-fifth to ninety-ninth percentiles. The wave variables were binary yes or no variables on each day. To capture any delayed effects we extended each wave seven days beyond its last day below the threshold. For example, if January 9 and 10 were days with temperatures below the cold threshold, then January 9 to 17 would have a value of 'yes' for cold wave.

To estimate the extra wave effects in each city we used,

$$\begin{aligned} d_t &\sim \text{Poisson}(\mu_t^*), \qquad t = 1, \dots, T, \\ \log(\mu_t^*) &= \log(\hat{\mu}_t) + \beta_1 C_t + \beta_2 H_t, \end{aligned} \tag{2}$$

where $\hat{\mu}_t$ is the estimated number of daily deaths from model (1), C_t is the binary variable indicating a cold wave day, and H_t is the binary variable indicating a heat wave day. The relative risk of death on cold wave days is therefore $\exp(\beta_1)$, and the relative risk of death on heat wave days is $\exp(\beta_2)$. Using this model (with $\hat{\mu}_t$ as an offset) ensures that these estimates are the extra wave effects after removing the general effects of temperature using model (1).

We averaged the relative risks and deviance across cities using a Bayesian model,

$$\begin{aligned} \hat{\beta}_{1,i} \sim \text{N}(\overline{\beta}_1, \hat{\sigma}^2_{1,i}), \qquad \hat{\beta}_{2,i} &\sim \text{N}(\overline{\beta}_2, \hat{\sigma}^2_{2,i}), \qquad i = 1, \dots, n, \\ \overline{\beta}_1 \sim \text{N}(0, 10^6), \qquad \overline{\beta}_2 &\sim \text{N}(0, 10^6), \end{aligned} \tag{3}$$

where $\hat{\beta}_{1,i}$ is the estimated cold wave effect in city i with estimated variance $\hat{\sigma}_{1,i}$ and n is the number of cities. The notation $\text{N}(\mu, \sigma^2)$ is a Normal distribution with mean μ and variance σ^2.

The key results are the means and 95% credible intervals for the average cold wave effect ($\overline{\beta}_1$) and average heat wave effect ($\overline{\beta}_2$). We calculated these estimates for a range of degrees of freedom and cold and heat waves definitions. We present estimates on the scale of the percentage change in mortality.

2.2. *Cold and heat wave characteristics*

To estimate the effects of the intensity, duration and timing of a cold and heat wave we replaced the regression equation (2) with,

$$\begin{aligned}\log(\mu_t^*) &= \log(\hat{\mu}_t) + \beta_1 C_t + \beta_2 CI_t + \beta_3 CD_t + \beta_4 CT_t + \\ &\quad \beta_5 H_t + \beta_6 HI_t + \beta_7 HD_t + \beta_8 HT_t,\end{aligned}$$

where CI_t is the cold wave intensity on day t, defined as the difference between the temperature on day t and the city's cold threshold, which is zero when the temperature is warmer than the threshold. CD_t is the duration of the cold wave, which is zero on the first day of the cold wave, one on the second day, two on the third day, and so on. CT_t is the timing of the cold wave, defined as the difference in days between day t and the start of the cool season on 1 October (this variable is zero on non-cold waves days). Similarly HI_t, HD_t and HT_t are the intensity, duration and timing of a heat wave, respectively. The timing of the heat wave is relative to the start of the warm season on 1 April.

We estimated the effects of the cold and heat wave characteristics in each city, and then averaged them using a similar Bayesian model (3).

2.3. *Other analyses*

The dependent variable in model (1) was the daily number of deaths for all ages excluding accidental and influenza deaths. We also examined deaths by age group (< 65, 65–74 and 75+ years), and respiratory and cardiovascular deaths for all ages.

To display the relative size of the temperature and wave effects we used Venn diagrams of the R-squared values for the percentage of variation in daily mortality accounted for by temperature and cold and heat waves. The R-squared values were estimated in each city and then averaged across cities. The estimates were calculated as the squared correlation between the predicted and observed number of daily deaths.

2.4. Estimation details

Models (1) and (2) were fitted using the glm library in R version 2.12.0, with the spline bases created using the dlnm library (Gasparrini et al., 2010). The Bayesian averages were calculated using WinBUGS version 1.4.3. We used a burn-in of 5,000 Markov chain Monte Carlo (MCMC) iterations followed by a sample of 5,000 (for an introduction to MCMC estimation see Dobson and Barnett (2008, Chapter 13)). The convergence of the chains were visually verified. The Venn diagrams were drawn using the VennDiagram library in R (Chen, 2011).

3. Results

Summary statistics on the number of cold and heat waves are in Table 1. The coldest cold wave had a median of just 10 waves per city during 1987–2000, and the hottest heat wave just 9 waves per city. The median number of deaths per city per day was 12, with an inter-quartile range of 7 to 21 (Supplementary Table 1).

Figure 1 shows the percent change in mortality for cold and heat waves for the five cold and five heat thresholds, when using 0 to 6 degrees of freedom for mean temperature. Heat waves had generally larger increases in deaths than cold waves, and there were even decreases in deaths at the coldest threshold. Heat waves based on the hottest threshold showed the largest increases in deaths. Increasing the degrees of freedom for mean temperature resulted in generally smaller effects for both cold and heat waves. This is because increasing the degrees of freedom better captures the non-linear changes in risk at temperature extremes.

The average cold and heat wave estimates for each threshold are in Table 2. For the coldest threshold there was a statistically significant decrease in deaths of –0.5% (95% CI: –0.9, –0.1%). For the hottest threshold there was a statistically significant increase in deaths of 1.6% (95% CI: 1.1, 2.1%).

The estimated changes in mortality associated with heat and cold waves were reasonably homogeneous when using four to six degrees of freedom per year to model season and time (Figure 2). The biggest difference was a slightly larger decrease in mortality at the coldest threshold for four degrees of freedom per year compared with six.

3.1. Results by age group and mortality type

The oldest age group had consistently larger increases in deaths associated with heat waves at all thresholds, and had the largest decrease in deaths at the coldest threshold (Figure 3).

Respiratory mortality showed a slightly larger decrease in deaths for most of the cold thresholds compared with cardiovascular mortality (Figure 4). The increase in deaths during heat waves was much greater for cardiovascular than respiratory mortality at the two hottest thresholds.

3.2. Cold and heat wave characteristics

The estimated effects of the characteristics of a cold and heat wave are in Table 3. There was no change in the effect of a cold wave depending on its intensity or duration. The increase in deaths associated with a cold wave declined over the cool season for the most extreme cold waves based on the 1st percentile of temperature. For every 50 days after October 1 the increases in deaths associated with a cold wave decreased by –1.26% (95% CI –0.03, –2.39%).

The increase in deaths associated with heat waves also appeared to decline over the warm season, although only for the hottest heat wave. For every 50 days after April 1 the increase in deaths associated with the hottest heat wave decreased by –0.77% (95% CI –1.56, 0.00%). There was a stronger association for more intense heat waves, and for longer heat waves based on the 95th percentile of temperature.

3.3. Shared and independent effects of waves and temperature

Venn diagrams of the average R-squared values for two thresholds and three or six degrees of freedom for mean temperature are in Figure 5. Most of the variance in daily mortality explained by cold waves was shared with mean temperature, with only a small independent part. The variance explained by heat waves was generally smaller than for cold waves, but with a larger relative proportion that was independent of temperature. The variance explained by cold and heat waves increased when using the relatively less extreme temperature percentiles (5th percentile for cold and 95th for heat). The independent variance explained by heat waves was reduced when using six degrees of freedom for mean temperature instead of three.

The same Venn diagrams for two randomly chosen cities (Coventry, Rhode Island and Toledo, Ohio) are in Supplementary Figure 2. The diagrams are similar to Figure 5, but show that the variance explained by cold or heat waves may be completely independent of that explained by mean temperature.

4. Discussion

Our results show that, on average, there is no added cold wave effect that goes beyond the known increased risk of cold temperatures (Table 2). We even found evidence of a reduction in daily deaths during the most extreme cold waves. This may be because people take better protective measures during extreme cold waves, such as avoiding travel and wearing warm clothing. The same cannot be said for extreme heat, as the risks increased for the more extreme heat waves (Figure 1). This suggests that the public are less able to deal with extreme heat than extreme cold. This may be because air conditioning is not always available (ONeill et al., 2005), or because the public does not fully appreciate the dangers of heat, and hence take appropriate precautions. Another explanation for the difference is that during cold weather people can wear extra clothes or stay indoors, but getting relief from hot weather can be more difficult, especially after every clothing layer has been removed, and especially for those without air conditioning.

The associations between cold waves and mortality depended on timing, with increased risks for cold waves earlier in the cool season (Table 3). Cold waves earlier in cool season may be more dangerous because of a build up in the susceptible pool towards the end of the warm season, which increases the size of the at-risk population (Frost and Auliciems, 1993). Another explanation is a reduced preparedness for cold weather early in the cool season, including preparations such as having fuel for home heating and warm clothes available.

The associations of heat waves also depended on timing, with possibly increased risks earlier in the warm season (although the change was smaller than that for cold timing, and the upper 95% credible interval was zero). As per the finding for cold waves, this could be explained either by an increased susceptible pool at the start of the warm season, or a reduced preparedness for hot weather. Further research is needed to delineate between these two competing hypotheses. This research is needed because if the susceptible pool hypothesis is true then there is little action that can be taken from a public health perspective. However, if the reduced preparedness hypothesis is true then there is the opportunity to intervene with public awareness campaigns at the start of the cold and warm seasons.

The impact of timing on the risk of cold and heat waves was relatively small (Table 3). Considering the susceptible pool hypothesis, this may be because deaths in this very frail group occur at less extreme temperatures. In support of this a study by Rocklöv et al. (2009) which examined the difference in summer mortality depending on the previous winter found the biggest changes for moderately hot summer temperatures rather than extreme hot temperatures.

We also found increased associations with mortality for more intense and longer lasting heat waves. Using the same data Anderson and Bell (2011) also found an increased risk of heat waves that were earlier in the season, more intense and longer lasting, and Gasparrini and Armstrong (2011) for longer lasting heat waves. The most likely explanation for these findings is that longer and more intense heat waves place a greater burden on the cardiovascular system. Days of sustained extreme high temperatures mean there is no chance for the cardiovascular system to rest during a day or two of cooler weather.

4.1. Modelling choices

An interesting problem is whether to model cold and heat wave effects as part of the general effects of temperature, or whether to model them as separate effects. Our results indicate that cold waves can be adequately captured by the smooth splines that are frequently used to model the health effects of temperature. The most extreme heat waves may have an independent effect, but this is relatively small compared with the amount of variance in daily mortality explained by mean temperature, and reduces when the spline for mean temperature is given more degrees of freedom (Figures 1 and 5, Supplementary Figure 2). This is because a more flexible spline is better able to capture the potentially sharp changes in risk due to heat waves. The key difference concerns the interpretation about whether the association is due to a defined heat wave or to high temperatures. Using heat waves may be appealing to some because they are potentially more understandable by policy makers and the public. The risk of this approach is that the dangers of high temperatures are perceived as only occurring above a temperature threshold. If the specific interest is in heat waves then we recommend estimating the combined risk of heat waves and high temperatures on heat wave days compared with non-heat wave days (Bobb et al., 2011).

Another modelling choice is whether to control for confounding by air pollutants. Pollutants such as nitrogen dioxide increase during winter because of the increased use of heaters. In initial analyses we controlled for nitrogen dioxide and the effects of temperature were not changed. For the sake of brevity we did not present those results.

4.2. Previous studies of extreme temperatures

Cold wave effects have been observed in previous studies, but without control for the general effects of low temperature (Revich and Shaposhnikov, 2008; Kysely et al., 2009; Montero et al., 2010; Revich and Shaposhnikov, 2010; Lin et al., 2011). In contrast with our study, the authors of a Spanish study reported an increased mortality with increased cold wave duration, and also that waves at the end of winter caused the greatest mortality, although with a wide variation in effect between waves (Montero et al., 2010). In Sweden there was no increase in the risk of death with persistent extreme cold (two or more days below the second percentile of temperature), but cold temperatures had a stronger effect early in the cold season (December) compared with later (February) (Rocklöv et al., 2011). In Taiwan deaths increased during prolonged heat, but not prolonged cold (Lin et al., 2011).

Previous studies of heat wave effects using the NMMAPS data have demonstrated small but statistically significant increases in mortality associated with heat waves. A 2.8% increase in daily deaths was reported using a heat wave definition of four or more consecutive days above the 99th percentile of temperature (Gasparrini and Armstrong, 2011), and a 3.7% increase was reported using a definition of three or more days above the 95th percentile (Anderson and Bell, 2011). These are larger than our estimated 1.6% increase in daily deaths (for two or more days above the 99th percentile) because both studies examined the effect of temperature and heat waves jointly, whereas our estimates were done in two stages to ensure that the wave effects were additional to the effects of mean temperature. Looking at the Venn diagrams (Figure 5), the additional wave effects are the areas not shared with temperature. Supplementary Figures 3 and 4 show the reduction in the size of the cold and heat effects when using a two-stage model (as per this paper) compared with a joint estimate (as per previous papers). We prefer the two-stage model as it gives the extra wave effects after accounting for the association between temperature and mortality.

4.3. Summary

On average we found no clear evidence for an extra effect of cold waves above the general effects of cold temperatures, although we stress that cold temperatures still pose a significant health problem. The effects of cold temperatures may be well described in the published literature, much of which did not model additional effects of cold waves.

There was an increased risk of death during heat waves. The largest increases were for the most extreme temperatures (Figure 1), although these extreme heat waves were also the rarest (Table 1). However, the public health burden of these extreme heat waves is very likely to increase as global temperature rise and extreme heat waves become more common (IPCC, 2007).

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Figure 1. Percent change in daily mortality associated with cold and heat waves according to the temperature percentile and degrees of freedom for mean temperature. Season and trend were modelled using six degrees of freedom per year. Based on 99 US cities for the years 1987–2000.

Figure 2. Percent change in daily mortality associated with cold and heat waves according to the temperature percentile and degrees of freedom per year for season and trend. Mean temperature was modelled using four degrees of freedom. Based on 99 US cities for the years 1987–2000.

Figure 3. Percent change in daily mortality associated with cold and heat waves according to the temperature percentile for the three age groups. Season and trend were modelled using six degrees of freedom per year, and mean temperature was modelled using four degrees of freedom. Based on 99 US cities for the years 1987–2000.

Figure 4. Percent change in daily cardiovascular and respiratory mortality associated with cold and heat waves according to the temperature percentile. Season and trend were modelled using six degrees of freedom per year, and mean temperature was modelled using four degrees of freedom. Based on 99 US cities for the years 1987–2000.

Figure 5. Venn diagrams of the R-squared values for mean temperature, cold waves and heat waves by the: degrees of freedom for mean temperature, and temperature percentile to define cold and heat waves. R-squared values are the percentage of variation in daily mortality accounted for by temperature and cold and heat waves. R-squared values were averaged across the 99 US cities (years 1987–2000).

Table 1: Summary statistics for the number of cold and heat waves, and the number of days classified as heat and cold wave days for the five temperature percentiles. Statistics are the median and inter-quartile range (in parenthesis) per city. Based on 99 US cities for the years 1987–2000.

Wave	Temperature percentile	Number of waves	Number of days
Cold	1 (coldest)	10 (9–12)	23 (20–26)
	2	19 (17–22)	50 (46–56)
	3	27 (24–29)	84 (76–88)
	4	32 (30–36)	116 (109–122)
	5	36 (34–42)	150 (140–157)
Heat	95	35 (31–38)	139 (126–152)
	96	31 (25–33)	109 (96–116)
	97	23 (19–26)	78 (67–82)
	98	17 (14–19)	44 (39–49)
	99 (hottest)	9 (8–11)	19 (17–23)

Table 2: Percent change in daily mortality associated with cold and heat waves for the five temperature percentiles. Season and trend were modeled using six degrees of freedom per year, and mean temperature was modeled using four degrees of freedom. Based on 99 US cities for the years 1987–2000.

Wave	Temperature percentile	Mean	95% CI
Cold	1 (coldest)	-0.5	$-0.9, -0.1$
	2	-0.1	$-0.4, 0.1$
	3	-0.1	$-0.3, 0.2$
	4	0.0	$-0.2, 0.2$
	5	0.1	$-0.1, 0.3$
Heat	95	0.0	$-0.2, 0.2$
	96	0.0	$-0.3, 0.2$
	97	0.0	$-0.2, 0.3$
	98	0.5	$0.2, 0.8$
	99 (hottest)	1.6	$1.1, 2.1$

CI = credible interval

Table 3: Percent changes in daily mortality associated with the cold and heat wave characteristics. Results for the lowest and highest temperature percentiles. Season and trend were modeled using six degrees of freedom per year, and mean temperature was modeled using four degrees of freedom. Based on 99 US cities for the years 1987–2000.

Characteristic (change)	Temperature percentile	Mean	95% CI
Cold intensity (5 $^\circ F$ lower)	1 (coldest)	0.07	$-0.18, 0.31$
	5	-0.06	$-0.17, 0.04$
Cold duration (5 days longer)	1	-0.05	$-0.70, 0.62$
	5	-0.12	$-0.26, 0.03$
Cold timing (50 days later†)	1	-1.26	$-2.39, -0.03$
	5	-0.18	$-0.46, 0.13$
Heat intensity (5 $^\circ F$ higher)	95	0.24	$0.03, 0.46$
	99 (hottest)	0.66	$0.12, 1.24$
Heat duration (5 days longer)	95	0.14	$0.01, 0.27$
	99	-0.52	$-1.39, 0.40$
Heat timing (50 days later‡)	95	-0.23	$-0.58, 0.15$
	99	-0.77	$-1.56, 0.00$

CI = credible interval

† Starting from October 1; ‡ Starting from April 1