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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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3 **Ethical approval**

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

6 1. Introduction

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

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

22 Due to global climate change there is much concern about the health impact of
23 heat waves. Thus, the most recent studies have investigated the additional effects
24 of current and future heat waves (D'Ippoliti et al., 2010; Rocklöv et al., 2011;
25 Anderson and Bell, 2011; Gasparrini and Armstrong, 2011; Peng et al., 2011).
26 There has been less work on cold waves, despite cold weather continuing to be a
27 significant health problem (Rocklöv et al., 2011), and the concern that climate
28 change will cause an increase in the intensity of winter storms (U.S. Climate
29 Change Science Program, 2008). A previous paper reported significant excess
30 all-cause mortality during cold spells in Holland (Huynen et al., 2001). Other
31 studies have also reported increased mortality risks during cold spells. However,
32 the underlying temperature response may not have been adequately controlled for,
33 meaning the observed increases are not necessarily due to wave effects
34 (Medina-Ramón and Schwartz, 2007; Revich and Shaposhnikov, 2008; Kysely
35 et al., 2009; Montero et al., 2010; Revich and Shaposhnikov, 2010). Also, unlike

36 with heat wave research, where it is known that characteristics such as heat wave
37 duration, intensity and timing during season are associated with the mortality
38 response, little is currently known about which characteristics of cold waves, if
39 any, are most relevant to public health.

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

48 **2. Materials and methods**

49 We used the US National Morbidity and Mortality Air Pollution Study
50 (NMMAPS) data from 1987–2000 (14 years) covering 108 cities (Samet et al.,
51 2000) (downloaded from <http://www.ihapss.jhsph.edu/data/data.htm>,
52 November 2010). To reduce the influence of missing data, we excluded cities with
53 more than 0.5% missing data for air or dew point temperature, which left 99 cities
54 (Supplementary Figure 1).

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

62 We used the following Poisson regression model in each city,

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

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

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

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

80 *2.1. Cold and heat waves*

81 We defined a cold wave as a temperature below a cold threshold for two or more
82 consecutive days. We tried a range of cold thresholds by using the first to fifth
83 percentiles of temperature in each city. This is a cold extreme relative the local
84 climate, an approach which has been shown to give more homogeneous effects in
85 the US (Anderson and Bell, 2010). A heat wave was similarly defined as a
86 temperature above a heat threshold for two or more consecutive days, with heat
87 thresholds from the ninety-fifth to ninety-ninth percentiles. The wave variables
88 were binary yes or no variables on each day. To capture any delayed effects we

89 extended each wave seven days beyond its last day below the threshold. For
 90 example, if January 9 and 10 were days with temperatures below the cold
 91 threshold, then January 9 to 17 would have a value of ‘yes’ for cold wave.

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

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

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

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

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

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

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

107 *2.2. Cold and heat wave characteristics*

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

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

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

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

121 *2.3. Other analyses*

122 The dependent variable in model (1) was the daily number of deaths for all ages
123 excluding accidental and influenza deaths. We also examined deaths by age group
124 (< 65 , $65-74$ and $75+$ years), and respiratory and cardiovascular deaths for all
125 ages.

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

132 *2.4. Estimation details*

133 Models (1) and (2) were fitted using the glm library in R version 2.12.0, with the
134 spline bases created using the dlnm library (Gasparrini et al., 2010). The Bayesian
135 averages were calculated using WinBUGS version 1.4.3. We used a burn-in of
136 5,000 Markov chain Monte Carlo (MCMC) iterations followed by a sample of
137 5,000 (for an introduction to MCMC estimation see Dobson and Barnett (2008,
138 Chapter 13)). The convergence of the chains were visually verified. The Venn
139 diagrams were drawn using the VennDiagram library in R (Chen, 2011).

140 **3. Results**

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

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

153 The average cold and heat wave estimates for each threshold are in Table 2. For
154 the coldest threshold there was a statistically significant decrease in deaths of
155 -0.5% (95% CI: $-0.9, -0.1\%$). For the hottest threshold there was a statistically
156 significant increase in deaths of 1.6% (95% CI: $1.1, 2.1\%$).

157 The estimated changes in mortality associated with heat and cold waves were
158 reasonably homogeneous when using four to six degrees of freedom per year to
159 model season and time (Figure 2). The biggest difference was a slightly larger

160 decrease in mortality at the coldest threshold for four degrees of freedom per year
161 compared with six.

162 *3.1. Results by age group and mortality type*

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

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

170 *3.2. Cold and heat wave characteristics*

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

177 The increase in deaths associated with heat waves also appeared to decline over
178 the warm season, although only for the hottest heat wave. For every 50 days after
179 April 1 the increase in deaths associated with the hottest heat wave decreased by
180 -0.77% (95% CI $-1.56, 0.00\%$). There was a stronger association for more intense
181 heat waves, and for longer heat waves based on the 95th percentile of temperature.

182 *3.3. Shared and independent effects of waves and temperature*

183 Venn diagrams of the average R-squared values for two thresholds and three or six
184 degrees of freedom for mean temperature are in Figure 5. Most of the variance in
185 daily mortality explained by cold waves was shared with mean temperature, with

186 only a small independent part. The variance explained by heat waves was
187 generally smaller than for cold waves, but with a larger relative proportion that
188 was independent of temperature. The variance explained by cold and heat waves
189 increased when using the relatively less extreme temperature percentiles (5th
190 percentile for cold and 95th for heat). The independent variance explained by heat
191 waves was reduced when using six degrees of freedom for mean temperature
192 instead of three.

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

197 **4. Discussion**

198 Our results show that, on average, there is no added cold wave effect that goes
199 beyond the known increased risk of cold temperatures (Table 2). We even found
200 evidence of a reduction in daily deaths during the most extreme cold waves. This
201 may be because people take better protective measures during extreme cold waves,
202 such as avoiding travel and wearing warm clothing. The same cannot be said for
203 extreme heat, as the risks increased for the more extreme heat waves (Figure 1).
204 This suggests that the public are less able to deal with extreme heat than extreme
205 cold. This may be because air conditioning is not always available (O'Neill et al.,
206 2005), or because the public does not fully appreciate the dangers of heat, and
207 hence take appropriate precautions. Another explanation for the difference is that
208 during cold weather people can wear extra clothes or stay indoors, but getting
209 relief from hot weather can be more difficult, especially after every clothing layer
210 has been removed, and especially for those without air conditioning.

211 The associations between cold waves and mortality depended on timing, with
212 increased risks for cold waves earlier in the cool season (Table 3). Cold waves
213 earlier in cool season may be more dangerous because of a build up in the
214 susceptible pool towards the end of the warm season, which increases the size of

215 the at-risk population (Frost and Auliciems, 1993). Another explanation is a
216 reduced preparedness for cold weather early in the cool season, including
217 preparations such as having fuel for home heating and warm clothes available.

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

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

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

242 *4.1. Modelling choices*

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

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

265 *4.2. Previous studies of extreme temperatures*

266 Cold wave effects have been observed in previous studies, but without control for
267 the general effects of low temperature (Revich and Shaposhnikov, 2008; Kysely
268 et al., 2009; Montero et al., 2010; Revich and Shaposhnikov, 2010; Lin et al.,
269 2011). In contrast with our study, the authors of a Spanish study reported an
270 increased mortality with increased cold wave duration, and also that waves at the

271 end of winter caused the greatest mortality, although with a wide variation in
272 effect between waves (Montero et al., 2010). In Sweden there was no increase in
273 the risk of death with persistent extreme cold (two or more days below the second
274 percentile of temperature), but cold temperatures had a stronger effect early in
275 the cold season (December) compared with later (February) (Rocklöv et al., 2011).
276 In Taiwan deaths increased during prolonged heat, but not prolonged cold (Lin
277 et al., 2011).

278 Previous studies of heat wave effects using the NMMAPS data have demonstrated
279 small but statistically significant increases in mortality associated with heat
280 waves. A 2.8% increase in daily deaths was reported using a heat wave definition
281 of four or more consecutive days above the 99th percentile of temperature
282 (Gasparrini and Armstrong, 2011), and a 3.7% increase was reported using a
283 definition of three or more days above the 95th percentile (Anderson and Bell,
284 2011). These are larger than our estimated 1.6% increase in daily deaths (for two
285 or more days above the 99th percentile) because both studies examined the effect
286 of temperature and heat waves jointly, whereas our estimates were done in two
287 stages to ensure that the wave effects were additional to the effects of mean
288 temperature. Looking at the Venn diagrams (Figure 5), the additional wave
289 effects are the areas not shared with temperature. Supplementary Figures 3 and 4
290 show the reduction in the size of the cold and heat effects when using a two-stage
291 model (as per this paper) compared with a joint estimate (as per previous
292 papers). We prefer the two-stage model as it gives the extra wave effects after
293 accounting for the association between temperature and mortality.

294 *4.3. Summary*

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

300 There was an increased risk of death during heat waves. The largest increases

301 were for the most extreme temperatures (Figure 1), although these extreme heat
302 waves were also the rarest (Table 1). However, the public health burden of these
303 extreme heat waves is very likely to increase as global temperature rise and
304 extreme heat waves become more common (IPCC, 2007).

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312 Anderson, G. B., Bell, M. L., 2010. Weather-related mortality: How heat, cold,
313 and heat waves affect mortality in the United States. *Epidemiology* **20**, 205–13.

314 Anderson, G. B., Bell, M. L., 2011. Heatwaves in the United States: Mortality risk
315 during heatwaves and effect modification by heatwave characteristics in 43 US
316 communities. *Environ Health Perspect* **119**, 210–8.

317 Barnett, A. G., Dobson, A. J., McElduff, P., Salomaa, V., Kuulasmaa, K., Sans,
318 S., WHO MONICA Project, 2005. Cold periods and coronary events: An
319 analysis of populations worldwide. *J Epidemiol Community Health* **59**, 551–7.

320 BBC News, 2009. More than 80 dead in European winter
321 weather <http://news.bbc.co.uk/1/hi/world/europe/8424953.stm> Accessed
322 28 January 2011.

323 Bobb, J. F., Dominici, F., Peng, R. D., 2011. A Bayesian model averaging
324 approach for estimating the relative risk of mortality associated with heat waves
325 in 105 U.S. cities. *Biometrics* In Press.

326 Chen, H., 2011. VennDiagram: Generate high-resolution Venn and Euler plots. R
327 package version 1.0.1.
328 URL <http://CRAN.R-project.org/package=VennDiagram>

329 D’Ippoliti, D., Michelozzi, P., Marino, C., de’Donato, F., Menne, B., Katsouyanni,
330 K., Kirchmayer, U., Analitis, A., Medina-Ramon, M., Paldy, A., Atkinson, R.,
331 Kovats, S., Bisanti, L., Schneider, A., Lefranc, A., Iniguez, C., Perucci, C., 2010.
332 The impact of heat waves on mortality in 9 European cities: results from the
333 EuroHEAT project. *Environ Health* **9**, 37.

334 Dobson, A. J., Barnett, A. G., 2008. An introduction to generalized linear models.
335 Chapman & Hall/CRC Press.

336 Frost, D. B., Auliciems, A., 1993. Myocardial infarct death, the population at risk,
337 and temperature habituation. *Int J Biometeorol* **37**, 46–51.

338 Gasparri, A., Armstrong, B., 2011. The impact of heat waves on mortality.
339 *Epidemiology* **22**, 68–73.

340 Gasparri, A., Armstrong, B., Kenward, M. G., 2010. Distributed lag non-linear
341 models. *Stat Med* **29**, 2224–34.

342 Gosling, S., Lowe, J., McGregor, G., Pelling, M., Malamud, B., 2009. Associations
343 between elevated atmospheric temperature and human mortality: a critical
344 review of the literature. *Climatic Change* **92**, 299–341.

345 Huynen, M. M., Martens, P., Schram, D., Weijenberg, M. P., Kunst, A. E., 2001.
346 The impact of heat waves and cold spells on mortality rates in the Dutch
347 population. *Environ Health Perspect* **109**, 463–70.

348 IPCC, 2007. Summary for policymakers. *Climate change 2007: The physical
349 science basis. Contribution of working group I to the fourth assessment report of
350 the Intergovernmental Panel on Climate Change. Tech. rep., Cambridge.*

351 Kysely, J., Pokorna, L., Kyncl, J., Kriz, B., 2009. Excess cardiovascular mortality
352 associated with cold spells in the Czech Republic. *BMC Public Health* **9**, 19.

353 Lin, Y.-K., Ho, T.-J., Wang, Y.-C., 2011. Mortality risk associated with
354 temperature and prolonged temperature extremes in elderly populations in
355 Taiwan. *Environmental Research* In Press.

356 Medina-Ramón, M., Schwartz, J., 2007. Temperature, temperature extremes, and
357 mortality: A study of acclimatization and effect modification in 50 US cities.
358 *Occup Environ Med* **64**, 827–33.

359 Montero, J., Mirón, I., Criado-Álvarez, J., Linares, C., Diaz, J., 2010. Mortality
360 from cold waves in Castile – La Mancha, Spain. *Sci Total Environ* **408**, 5768–74.

361 O'Neill, M., Hajat, S., Zanobetti, A., Ramirez-Aguilar, M., Schwartz, J., 2005.
362 Impact of control for air pollution and respiratory epidemics on the estimated
363 associations of temperature and daily mortality. *Int J Biometeorol* **50**, 121–9.

364 Peng, R. D., Bobb, J. F., Tebaldi, C., McDaniel, L., Bell, M. L., Dominici, F.,
365 2011. Towards a quantitative estimate of future heat wave mortality under
366 global climate change. *Environ Health Perspect* **119**, 701–6.

367 Revich, B., Shaposhnikov, D., 2008. Excess mortality during heat waves and cold
368 spells in Moscow, Russia. *Occup Environ Med* **65**, 691–6.

369 Revich, B. A., Shaposhnikov, D. A., 2010. Extreme temperature episodes and
370 mortality in Yakutsk, East Siberia. *Rural Remote Health* **10**,
371 <http://www.rrh.org.au>.

372 Rocklöv, J., Ebi, K., Forsberg, B., 2011. Mortality related to temperature and
373 persistent extreme temperatures: a study of cause-specific and age-stratified
374 mortality. *Occup Environ Med* **68**, 531–6.

375 Rocklöv, J., Forsberg, B., Meister, K., 2009. Winter mortality modifies the
376 heat-mortality association the following summer. *European Respiratory Journal*
377 **33**, 245–51.

378 Samet, J., Zeger, S., Dominici, F., Curriero, F., Coursac, I., Dockery, D., et al,
379 2000. The National Morbidity, Mortality, and Air Pollution Study. Part II:
380 Morbidity and mortality from air pollution in the United States. *Health Effects*
381 *Institute*.

382 The Eurowinter Group, 1997. Cold exposure and winter mortality from ischaemic
383 heart disease, cerebrovascular disease, respiratory disease, and all causes in
384 warm and cold regions of Europe. *Lancet* **349**, 1341–6.

385 U.S. Climate Change Science Program, 2008. Weather and climate extremes in a
386 changing climate. Regions of focus: North America, Hawaii, Caribbean, and
387 U.S. Pacific Islands. Tech. rep., Department of Commerce, NOAA's National
388 Climatic Data Center, Washington, D.C., USA.

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

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

397 Figure 3. Percent change in daily mortality associated with cold and heat waves
398 according to the temperature percentile for the three age groups. Season and
399 trend were modelled using six degrees of freedom per year, and mean temperature
400 was modelled using four degrees of freedom. Based on 99 US cities for the years
401 1987–2000.

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

407 Figure 5. Venn diagrams of the R-squared values for mean temperature, cold
408 waves and heat waves by the: degrees of freedom for mean temperature, and
409 temperature percentile to define cold and heat waves. R-squared values are the
410 percentage of variation in daily mortality accounted for by temperature and cold
411 and heat waves. R-squared values were averaged across the 99 US cities (years
412 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 °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 °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