Int J Biometeorol (2012) 56:569–581
DOI 10.1007/s00484-011-0497-3

REVIEW

Daily average temperature and mortality among the elderly: a meta-analysis and systematic review of epidemiological evidence

Weiwei Yu · Kerrie Mengersen · Xiaoyu Wang · Xiaofang Ye · Yuming Guo · Xiaochuan Pan · Shilu Tong

Received: 24 February 2011 / Revised: 12 September 2011 / Accepted: 12 September 2011 / Published online: 6 October 2011
© ISB 2011

Abstract The impact of climate change on the health of vulnerable groups such as the elderly has been of increasing concern. However, to date there has been no meta-analysis of current literature relating to the effects of temperature fluctuations upon mortality amongst the elderly. We synthesised risk estimates of the overall impact of daily mean temperature on elderly mortality across different continents. A comprehensive literature search was conducted using MEDLINE and PubMed to identify papers published up to December 2010. Selection criteria including suitable temperature indicators, endpoints, study-designs and identification of threshold were used. A two-stage Bayesian hierarchical model was performed to summarise the percent increase in mortality with a 1°C temperature increase (or decrease) with 95% confidence intervals in hot (or cold) days, with lagged effects also measured. Fifteen studies met the eligibility criteria and almost 13 million elderly deaths were included in this meta-analysis. In total, there was a 2–5% increase for a 1°C increment during hot temperature intervals, and a 1–2 % increase in all-cause mortality for a 1°C decrease during cold temperature intervals. Lags of up to 9 days in exposure to cold temperature intervals were substantially associated with all-cause mortality, but no substantial lagged effects were observed for hot intervals. Thus, both hot and cold temperatures substantially increased mortality among the elderly, but the magnitude of heat-related effects seemed to be larger than that of cold effects within a global context.

Keywords Elderly · Meta-analysis · Mortality · Systematic review · Temperature

Abbreviations

CI	Credible interval
GDP	Gross domestic product
MCMC	Markov chain Monte Carlo
MMT	Minimum mortality temperature

Introduction

An increasing number of epidemiological studies have found that variation in temperature is closely associated with mortality in many parts of the world (Anderson and Bell 2009; Baccini et al. 2008; Basu et al. 2005; Hajat et al. 2005; Kan et al. 2007; Kysely et al. 2009; McMichael et al. 2008; Stafoggia et al. 2008). Outcomes include all-cause mortality (Baccini et al. 2008; Hajat et al. 2005; McMichael et al. 2008), cause-specific mortality (Basu et al. 2005; Kysely et al. 2009) or both (Anderson and Bell 2009; Kan et al. 2007; Stafoggia et al. 2008). Temperature indicators have included daily minimum,

W. Yu · X. Wang · X. Ye · Y. Guo · S. Tong (✉)
School of Public Health and Institute of Health and Biomedical Innovation, Queensland University of Technology, Kelvin Grove, QLD 4059, Brisbane, Australia
e-mail: s.tong@qut.edu.au

K. Mengersen
Discipline of Mathematical Sciences, Faculty of Science and Technology, Queensland University of Technology, Brisbane, Australia

X. Pan
School of Public Health, Peking University, Beijing 100191, China

W. Yu (✉)
School of Public Health, Queensland University of Technology, Kelvin Grove, QLD 4059, Australia
e-mail: weiwei.yu@qut.edu.au

maximum, average, apparent or diurnal temperature (Baccini et al. 2008; Bell et al. 2008; Goodman et al. 2004; Hajat et al. 2007; Kan et al. 2007; Kim and Joh 2006; Michelozzi et al. 2006; Stafoggia et al. 2009). Generally, all-cause mortality is often used to avoid the common misclassification of temperature-related mortality (Hajat and Kosatsky 2010). Average temperature experienced throughout the whole day and night usually provides more easily interpreted results within a policy context (Anderson and Bell 2009).

The relationship between temperature and mortality is commonly described as a “U”, ”V”, or “J” shape (Armstrong 2006; Braga et al. 2002). Investigations of the association between temperature and mortality have often presumed a log-linear model below or above a threshold (Curriero et al. 2002; Hajat et al. 2007; McMichael et al. 2008). The threshold level is generally defined as the optimum temperature corresponding to the minimum level of mortality (Kalkstein and Davis 1989). The slopes on two sides of the minimum mortality temperature (MMT) are highly dependent on the selected threshold (Armstrong 2006). The percent increase in mortality has often been used as the effect estimate in interregional comparisons for both hot- and cold-related mortality (The Eurowinter Group 1997).

Many studies have observed that changes in average temperature have a larger impact on mortality among the elderly compared to younger people (Ballester et al. 1997; Basu et al. 2005; Carder et al. 2005; Curriero et al. 2002; Donaldson and Keatinge 2003; El-Zein et al. 2004; Gouveia et al. 2003; Hajat et al. 2005; Hajat et al. 2007; Ishigami et al. 2008; Kim et al. 2006; Michelozzi et al. 2000; Revich and Shaposhnikov 2008; Rocklöv and Forsberg 2008; The Eurowinter Group 1997). This difference has in part been attributed to the reduced ability of older adults to maintain core temperature. The reduced sweat gland output, reduced skin blood flow, smaller increase in cardiac output and less redistribution of blood flow from renal and splanchnic circulations can consequently aggravate the injury to thermoregulation (Basu 2009; Bouchama and Knochel 2002; McGeehin and Mirabelli 2001). In addition, other factors such as living conditions including air conditioning, family and/or social support as well as access to medical care systems can be modifiers of temperature-related effects on elderly mortality (Stafoggia et al. 2008).

The concern about the health impacts of climate change has increased over the last few decades (Tong 2000). The wide variation in study location and climatic conditions, along with inconsistent results of temperature effects on elderly mortality indicates that there is a need to quantify the overall risk of death among the elderly associated with temperature changes.

Meta-analysis is a useful statistical tool for assessing the nature, overall magnitude and major features of an exposure-outcome relationship on the basis of multiple independent studies (Nam et al. 2003). In addition, a systematic approach to synthesise recent research results can provide information for timely and urgent decisions in public health, and also provide evidence of the effectiveness of health care interventions and policies (Stroup et al. 2000).

Recent meta-analysis research into the association between temperature and mortality has attempted to estimate the average risk level from a variety of locations by analysing specific regional data first, the results of which are then combined directly (Analitis et al. 2008; Medina-Ramón and Schwartz 2007) or within specific geographical regions (e.g. Mediterranean and north-continental regions) (Baccini et al. 2008). Since data related to specific cities are not always available for analysis, Hajat and Kosatsky (2010) recently provided an elegant substitutive method to perform the meta-analysis on temperature and mortality by generalising published literature throughout the world. However, this study was focused on the general population rather than the elderly for both hot and cold effects.

It has been increasingly recognised that temperature can affect the number of deaths occurring on not only the same day, but also on several subsequent days (Armstrong 2006; Muggeo and Hajat 2009). To date, no uniform method has been confirmed to identify the relevant lag periods. Investigation of such lagged effects has focused on antecedent days (Muggeo and Hajat 2009) or a particular day with the strongest association between temperature and mortality (Kysely et al. 2009). Distributed-lag models have been used to explore lag structures (Analitis et al. 2008; Baccini et al. 2008; Hajat et al. 2005) and to assess the lagged effects of temperature on mortality (Armstrong 2006).

In this study, a two-stage Bayesian hierarchical model was developed to combine relevant temperature-mortality studies over different lags and to quantify increased mortality among the elderly associated with changes in daily mean temperature across different regions.

Materials and methods

Strategy for literature searching

Peer-reviewed studies concerning temperature and mortality among the elderly were identified using the MEDLINE and PubMed databases. Medicine’s Medical Subject Headings (MeSH) terms which included “weather”, “temperature”, “hot temperature” , “cold temperature”, “mortality”, “death”, “ frail elderly” and “aged” were used, and studies published up to December 2010 (the date when the literature was undertaken) were considered. References in each identified paper were also closely examined to check if any paper was missed in the electronic database searches.

Study eligibility

The following eligibility criteria were used in this study:

- The exposure indicator was daily mean temperature and the outcome measure was all-cause mortality.
- A time series or case-crossover study design was used.
- The elderly group was observed separately. Most studies included in this meta-analysis defined the elderly as people aged over 65 years although the definition varied slightly in several studies (Ballester et al. 1997; Ishigami et al. 2008; Revich and Shaposhnikov 2008; The Eurowinter Group 1997).
- The hot or cold threshold was reported or the temperature effect was analysed by seasons. Studies of weather extremes (e.g. heat waves or cold spells) were not included in this meta-analysis because they usually explored health effects of a special event.
- The reported results included the effect estimate associated with a one unit increase or decrease of temperature. An outcome measure was reported as either: relative risk, regression coefficient or percent change. Standard errors or 95% credible intervals (CIs) were reported.

Data extraction

The quantitative estimates of each study which met the eligibility criteria were retrieved and carefully checked to guarantee the validity of the extraction. Three reviewers used a standardised spreadsheet to independently abstract data on study methods and details of studied populations, exposure measures, health outcomes, and confounders. Disagreements remaining after contact with authors were resolved by consensus.

The effect estimates reported in each study were transformed into the percent change in deaths per °C increase (or decrease) in daily average temperature if different scales were used (such as per 10°F) (Basu et al. 2005). We contacted authors of some included studies to request additional data and clarify their methods as necessary.

Temperature intervals

Meta-analysis was performed within several temperature intervals. We selected temperature intervals from the overlaps of the hot or cold ranges in various cities included. For each city, we identified the hot range according to its hot threshold and maximum mean temperature, and its cold range according to its minimum mean temperature and cold threshold. For seasonal studies (Basu et al. 2005; Michelozzi et al. 2000), we used the maximum mean temperature minus minimum mean temperature in summer or winter as the hot or cold range.

We assigned seven temperature intervals: 0–5°C, 5–11°C, 11–15°C for cold studies, 20–25°C, 25–28°C and over 28°C for hot studies, and 15–20°C for both hot and cold studies. Thus, a single city can be included in multiple temperature intervals. For example, the study of Stockholm with the range of 12–26°C was included in the hot interval of 15–20°C, and was also included in the hot interval of 20–25°C.

Meta-analysis

The results in each temperature interval were combined using a two-stage Bayesian hierarchical model. The first level of the hierarchy comprised the repeated effect estimates from each study. Most studies gave more than one estimate of the temperature effects, based on different specific means, lags, or elderly subgroups. These results were combined to give an overall effect for each study as described below. At the second level of the hierarchy the study means were combined to give an overall mean effect.

More formally, the hierarchical model can be described as follows:

$$\begin{aligned}
&o_{i,j} \sim N(\mu_{i,j}, \sigma^2_{i,j}), \qquad i = 1, \ldots, n, j = 1, \ldots, m_i, \\
&\mu_{i,j} \sim N(\delta_i, \tau^2_i), \\
&\delta_i = \vartheta_i + lag_i \\
&\vartheta_i \sim N(\upsilon_b, \psi^2_b).
\end{aligned} \tag{1}$$

In this model, the jth observed effect estimate in the ith study is denoted by $o_{i,j}$ with associated variance $\sigma^2_{i,j}$. The observed effect has a jth result-level mean $\mu_{i,j}$, which is assumed to be normally distributed around a true result-level mean δ_i with an estimated variance of τ^2_i (the variance between estimates within the ith studies). The true result-level mean depends upon the study mean (ϑ_i) and a lagged effect. The study means are centred around an overall mean, υ_b and their spread is controlled by the between-study variance, ψ^2_b.

The lagged effect is described by a distributed-lag model defined by days as follows:

$$lag_i = \sum_{k=1}^{d} a_k l_i^k,\ l \in [0, q_i] \tag{2}$$

where d is the degrees of freedom, l is the lag days and q_i is the maximum number of lag days reported in the ith study (Braga et al. 2002; Goodman et al. 2004). We chose d=4 in this study to obtain a reasonably flexible distribution of lags and parsimony in the number of parameters estimated (Armstrong 2006; Hastie and Tibshirani 1990). Thus Eq. 1 can be estimated by up to a fourth-order polynomial in l_i, as:

$$\delta_i = \vartheta_i + a_1 l_i + a_2 l_i^2 + a_3 l_i^3 + a_4 l_i^4 \quad (3)$$

Four regression models (d=1, 2, 3, 4) were fitted using eligible data identified in each temperature interval, with the lag assumed to have a first, second, third or fourth-order polynomial trend. We used a reference level of zero days for exposure lag. Uninformative conjugate priors were applied to all parameters (e. g. lag, study mean, overall mean and observed effect). The best model for each temperature interval was selected on the basis of the deviance information criterion.

The models were fitted using the WinBUGS software (Spieghalter et al. 1995). We used a burn-in of 3,000 Markov chain Monte Carlo (MCMC) iterations, followed by a sample of 15,000 iterations for each model. Convergence was based on the stability of the trace plots and posterior distributions of the parameters, and autocorrelation between iterations available in WinBUGS.

Results

We identified 786 citations from searches of electronic bibliographic databases and additional references cited from other sources. We retrieved the abstracts of 362 studies for detailed evaluation of which 144 articles were examined in full, eventually resulting in 15 studies being included in the review (Table 1). Figure 1 shows the details of the literature identification process.

Table 1 Summary information for the studies included

Reference	Study regions and period	Age	No. of daily deaths	Category	Threshold (°C)	Temperature interval (°C)	Covariates
Revich and Shaposhnikov 2008	Moscow 2000–2006	>75	141	Cold Heat	18 18	−10 to18 18–25	Season
Rocklöv and Forsberg 2008	Stockholm 1998–2003	≥65	373	Heat	12	12–26	Influenza, season, holidays week day, time
Ishigami et al. 2008	Budapest, 1993–2001 London, 1993–2003 Milan, 1999–2004	≥75	55 136 26	Heat	24.4 20.4 26.3	24.4–31 20.4–28 26.3 –33	Day of the week, holidays PM_{10},O_3,time
Hajat et al. 2007	England and Wales 1993–2003	≥65	950	Cold Heat	5 18	−10 to 5 18–25	Influenza, PM_{10},O_3,time
Kim et al. 2006	6 Korean cities 1994–2003	≥65	131	Heat	24.3–30.2	24.3–34	Day of the week, Holidays, humidity
Basu et al. 2005	20 US cities, 1992	≥65	466	Winter Summer	- -	−22 to 25.6 9.1–33.2	PM_{10},O_3,time
Hajat et al. 2005	London,1991–1994 Delhi,1991–1994 Sao Paulo,1991–1994	≥65	177 100 170	Heat	20 20 20	20–28 20–36 20–27	Rainfall, PM_{10}, humidity, day of the week, holidays, time
Carder et al. 2005	3 Scottish cities 1981–2001	≥65	51	Cold	11	−10 to 11	Black smoke
El–Zein et al. 2004	Greater Beirut 1997–1999	≥65	5.5	Cold Heat	27.5 27.5	5–27.5 27.5–31	Year, season, day of the week, holidays
Donaldson and Keatinge 2003	England and Wales 1998–2000	≥65	950	Cold	18	0–18	Influenza
Gouveia et al. 2003	Sao Paulo 1991–1994	≥65	69	Cold Heat	20 20	7–20 20–27	Humidity, PM_{10},O_2,SO_2,CO, NO2, day of the week, holidays, time
Curriero et al. 2002	11 United States cities 1973–1994	≥65	492	Cold Heat	21–27.9 21–27	−3.6 to 27.9 21–33	Time
Michelozzi et al. 2000	Rome 1987–1996	≥65	15	Summer	-	9.6–30.2	Time, day of the week, holidays, population
Ballester et al. 1997	Valencia 1991–1993	>70	12	Cold Heat	15 24	5–15 24–31	Influenza, humidity, Black smoke, day of the week holidays
The Eurowinter Group 1997	8 European cities 1988–1992	≥50	262	Cold	18	0–18	Influenza

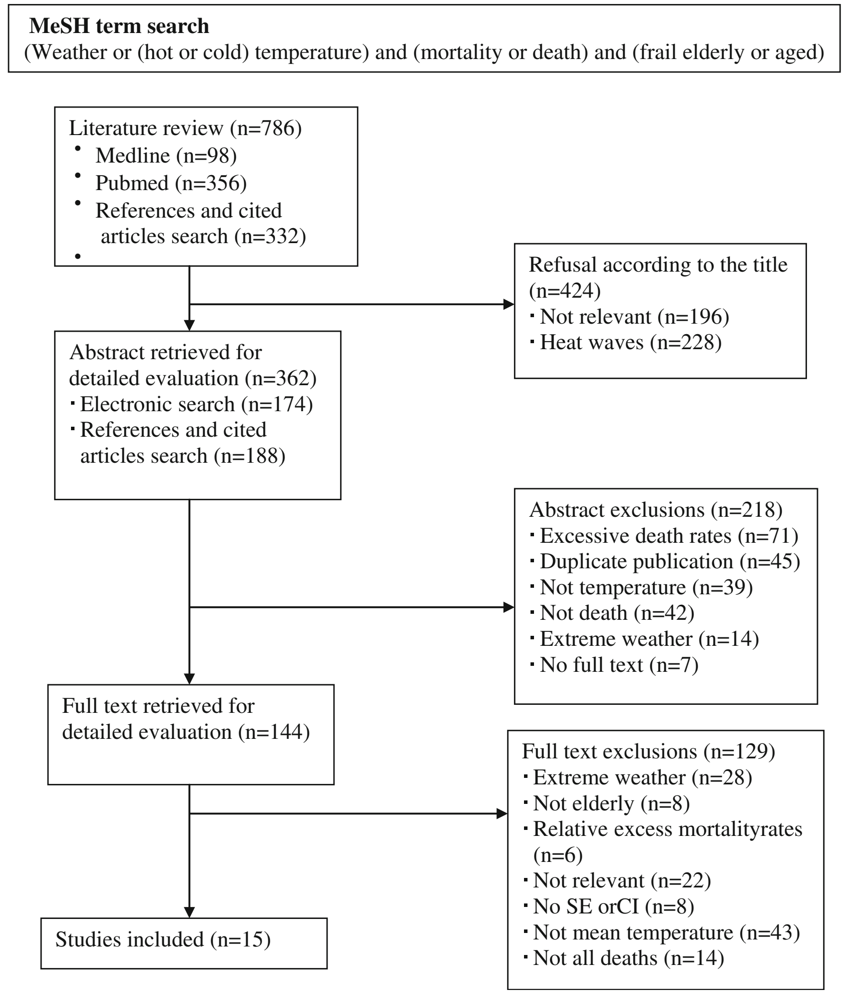


Fig. 1 Procedure of literature search

Characteristics of studies included

Among the 15 studies that met the eligibility criteria, five focused on hot effects, three on cold effects and the other seven on both. In total, these studies comprised almost 13 million elderly deaths. The thresholds ranged from 18°C to 30.2°C for hot effects and 5°C to 27.5°C for cold effects across different continents. The hot temperatures ranged from 18°C to 36°C and the cold temperatures ranged from −22°C to 27.9°C (Table 1). The selected studies covered four continents: Europe, North America, South America and Asia. Three main climate zones were included, namely, arid, warm temperate and snow according to the Köppen-Geiger climate classification (Fig. 2) (Kottek et al. 2006).

For hot effects, 37 cities and regions were included and lag times varied among 0, 1, 2, 6, 7, 14 and 28 days. Fifty-two of the 80 estimates were statistically significant ($P<0.05$), with a maximum of 25.7% (95% CI, 16.2–35.2) and a minimum of 1.20% (95% CI, 1.10–1.30) increase in mortality per degree rise in temperature above the threshold (Fig. 3a). In the studies of cold effects, 36 cities and regions were included and lag times varied among 0, 2, 3, 6, 14, 20 and 30 days. Among 69 estimates, 44 were statistically significant ($P<0.05$) with the 0.05% (95% CI, 0.01–0.09) to 8.5% (95% CI, 5.44–11.56) in mortality per degree decrease below the threshold (Fig. 3b). For both hot and cold effects, the 95% confidence intervals based on 20 U.S. cities seemed wider than those in other places which may be due to the fact that only data in 1992 were used (Basu et al. 2005). As part of a sensitivity analysis, we compared the meta-analysis results with and without this study, and no fundamental differences were observed.

Across all studies included, the latitude ranged from 25.77° N to 64° N with the exception of one study from the southern hemisphere in Brazil with latitude 23.5° S (Gouveia et al. 2003). As indicated in Fig. 4, the regression lines for both hot and cold thresholds show that there was a positive relation between thresholds of mortality and mean temperature, and there was an apparent trend towards lower thresholds in higher-latitude areas and higher thresholds in lower-latitude areas. The relationship between mean temperature and latitude shows that higher latitude areas usually experienced lower temperatures.

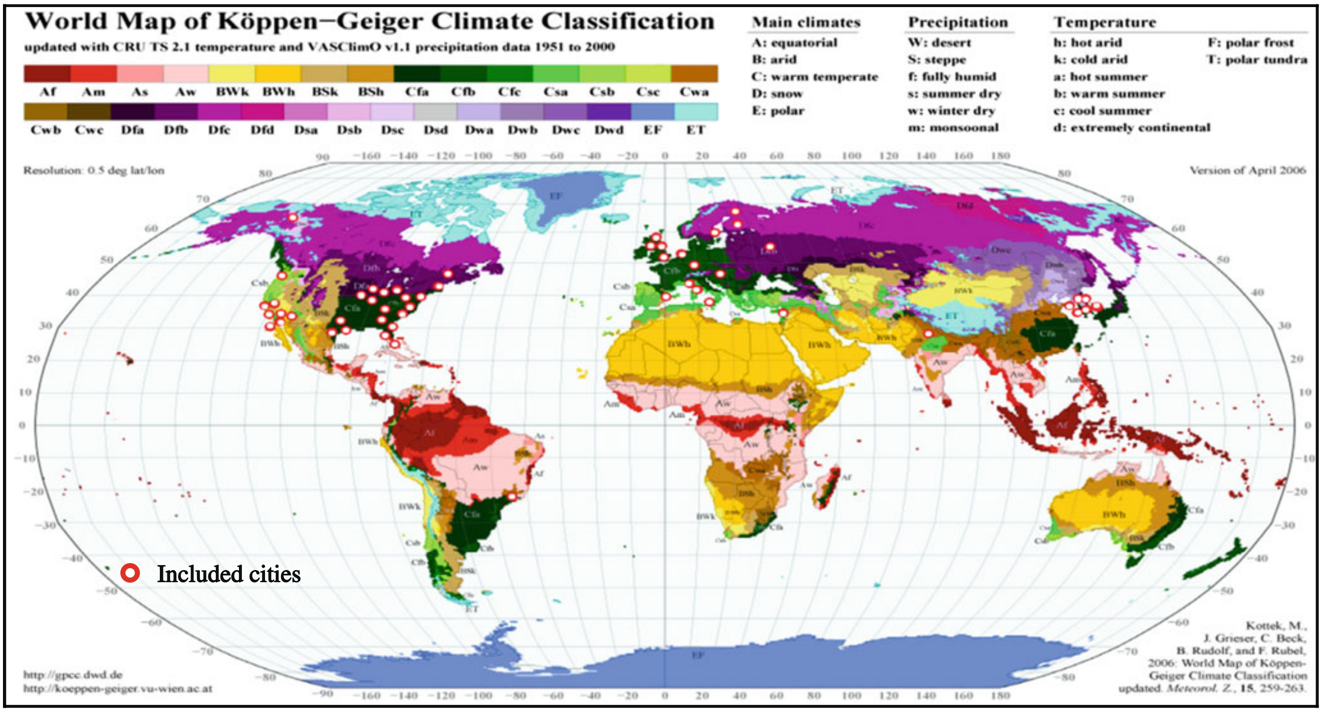


Fig. 2 The cities (*red circles*) and the climate zones included in the meta-analysis. Source: adopted from http://www.borntraeger-cramer.de (with the publisher's permission)

However, there was considerable variation in mean temperature along a single line of latitude. European cities were generally warmer than other areas of the same latitude around the globe due to the fact that Europe is warmed by an ocean stream from the Gulf of Mexico. For example, Washington had a much lower average temperature (2.22°C) than Palermo although their latitudes were very similar (around 38° N) (Fig. 4).

In terms of threshold temperatures, a noticeable exception about the threshold was that some locations at different latitude and mean temperature had the same threshold. For example, although the latitude varied from 37.98° in Oakland (Basu et al. 2005) to 64.18° in South Finland (The Eurowinter Group 1997) and the mean temperature varied from −2.8°C in North Finland to 15.4°C in Palermo, the same threshold of 18°C was reported (Fig. 4).

Meta-analysis

Overall, the effect estimates in hot intervals were more than twice those in cold intervals although no substantial association was identified for the temperature intervals of 0–5°C (cold) and 15–20°C (both hot and cold). For hot effects, the temperature interval of 25–28°C had a similar percent increase (2.67%; 95% CI, 0.36–4.81) compared with the neighbouring period of 20–25°C (2.85%; 95% CI, 1.65–4.41). The largest effect estimate was for temperatures higher than 28°C with an increase of 5.08% (95% CI, 1.07–9.32) in elderly deaths with one degree increase in mean temperature. The percent increase was smallest in the interval of 11–15°C for cold effects (0.92%; 95% CI, 0.07–1.83) (Fig. 5).

Regarding the lagged effects, first and second-order polynomial models were selected for all temperature intervals. Only in the interval of 5–11°C did the temperature/mortality have a substantial association with lag days (95% CI did not include zero). As shown in Table 2, the 95% CI corresponding to lags up to 9 days in exposure to cold temperature did not include zero, but the corresponding CI for exposure to hot intervals did include zero. We did not observe substantial between-study variances except for temperature intervals of 11–15°C, 15–20°C (cold), 20–25°C and >28°C (Table 2). There were substantial within-study variances among the temperature intervals of 5–11°C, 11–15°C, 15–20°C (cold) and 15–20°C (hot).

Discussion

This is the first attempt to quantify, using a systematic approach, the temperature-related mortality among the elderly across different continents, a group shown to be vulnerable to both hot and cold temperature fluctuation. In

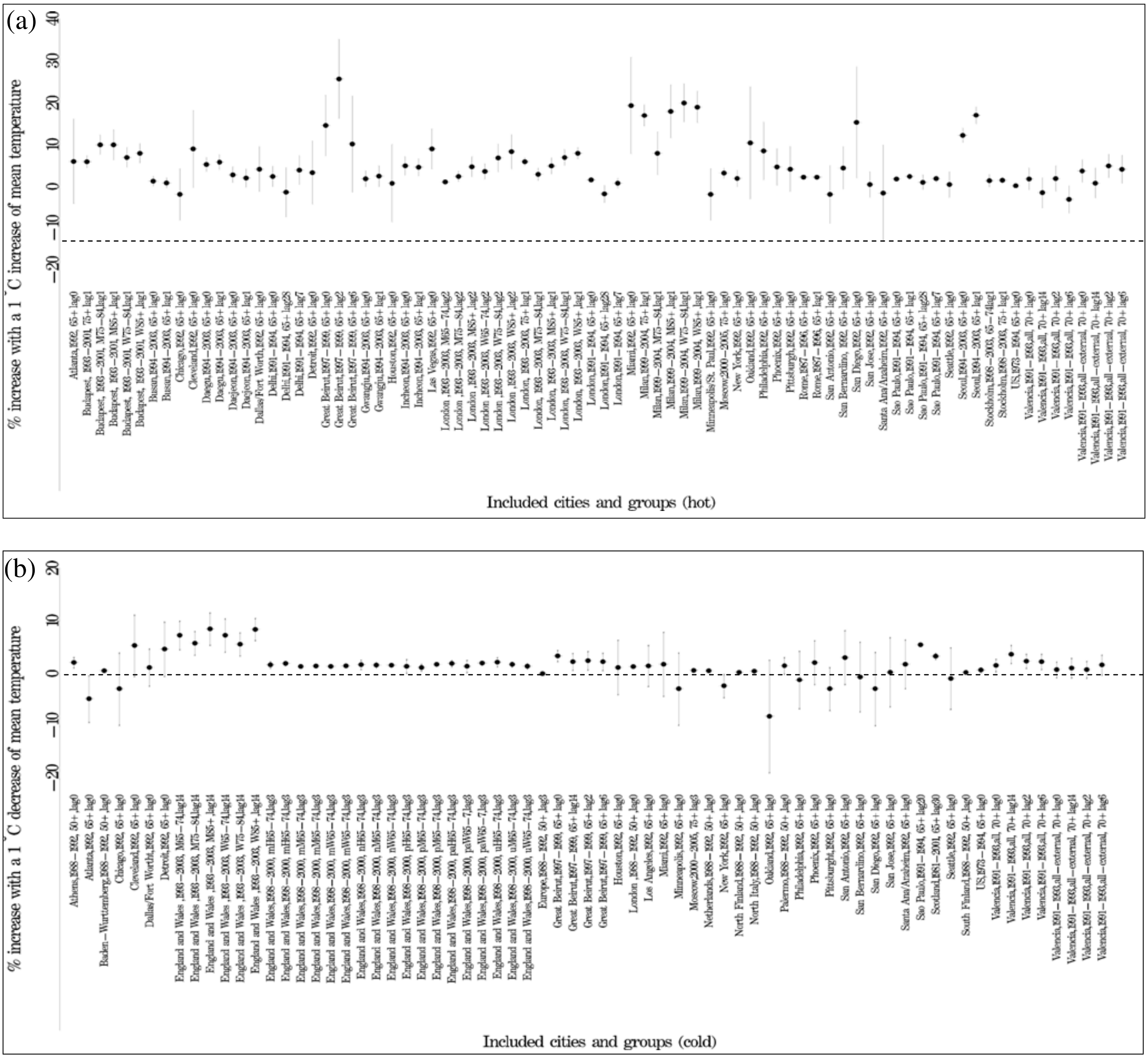


Fig. 3 Percent increases in daily deaths among the elderly with one degree decrease or increase of mean temperature reported in published studies of hot (**a**) and cold (**b**) effects. Abbreviations: *W* woman, *M* man, *H* housewives, *m* managerial and technical, *n* non-manual skilled, *pa* partly skilled, *p* professional, *u* unskilled

this meta-analysis, we considered elderly deaths in diverse locations and found a substantial association between daily mean temperature and mortality for both hot and cold temperature intervals. On the basis of the epidemiological evidence, we found that there was a 2–5% increase in all-cause mortality for a 1°C increment during hot temperature intervals and a 1–2% increase in all-cause mortality for a 1°C decrease during cold temperature intervals. Lags up to 9 days in exposure to cold temperature intervals were significantly associated with all-cause mortality, but no substantial lagged effects were observed for hot intervals.

Comparison with other studies

The observation of percent increases in the whole temperature band exhibits stronger hot effects than cold effects. The results suggest that climate change will play an increasingly significant role in temperature-related mortality, particularly among the elderly. Climate change is projected not only to increase the global average temperature by between 1.1°C and 6.4°C by 2100, but also to change the frequency of extreme weather events, with the increasing number of extremely hot days and the decreasing number of extremely cold days (Medina-Ramón and Schwartz 2007).

However, there is no consensus whether decreases in cold-related mortality as a result of global warming will compensate for increases in heat-related mortality (Medina-Ramón and Schwartz 2007). Our results corroborate the report by Medina-Ramón and Schwartz (2007), which states that as climate change continues, increases in heat-related mortality are likely to greatly outweigh decreases in cold-related mortality. However, the fact that a 1°C decrease in mean temperature increased elderly deaths by 1–2% adds evidence that cold-related mortality is still an important public health problem which requires attention (Analitis et al. 2008).

Our findings imply that the cold effects may last longer than the hot effects. Heat-related mortality seems to be an acute event among people with advanced forms of illness (e.g., myocardial infarction and stroke) who may be expected to die anyway within a short period (Muggeo and Hajat 2009), while cold-related effects can continue to exhibit an influence on less acute mortality rates (e.g. respiratory mortality) from days to weeks (Braga et al. 2002; Goodman et al. 2004; Gouveia et al. 2003; Pattenden et al. 2003). In this study, the effects of colder temperatures persisted for approximately 9 days for temperature intervals of 11–15°C.

The minimum mortality temperature (MMT) is the key factor in analysing temperature-mortality data since it determines the magnitude of the estimated risk below or above the MMT (Basu 2009; Kalkstein and Davis 1989). Generally, MMT is closely related to local climate because of population acclimatisation and adaptation facilities (Hajat et al. 2002; Lorenzo et al. 1999). As indicated in Fig. 4, MMT has a positive association with local mean temperature. It is lower in the cities with higher latitude and higher in the cities with lower latitude. This pattern is consistent with more effective adaptation to colder temperatures in higher-latitude areas and to hotter temperatures in lower-latitude areas (Analitis et al. 2008; Baccini et al. 2008). The results were similar to those reported in a previous meta-analysis, in which higher heat thresholds were found in those populations accustomed to higher summertime temperatures (Hajat and Kosatsky 2010).

Moreover, locations which differ widely in socio-economic status may have different threshold temperatures even if their climate and latitude are similar (Hajat and Kosatsky 2010). That is, people may become less sensitive to the effects of temperature as a consequence of advancing economic development (McMichael et al. 2008). For example, in this study, since a number of locations with different latitudes had the same threshold (18°C), it illustrates that socioeconomic conditions may play a significant role in the temperature-mortality relationship. In addition, due to the awareness of adverse effects of climate change, especially after several severe heat waves (Conti et al. 2007; Fouillet et al. 2008; Kaiser et al. 2007), effective preventive policies such as heat health warning systems in both Europe and the United States may have markedly reduced excess deaths in extremely hot weather (Ebi et al. 2004; Kaiser et al. 2007).

We have also noticed that cities in Korea have higher heat thresholds than US and European cities with similar latitudes and mean temperatures. As the GDP per capita of Korea is generally lower than those countries (World Bank 2001), this suggests that cultural and demographic characteristics may also affect MMT. Moreover, urban heat islands and the building's environment (e.g. heating and air conditioning) may also modify the MMT and the effect of temperature on mortality (Hajat and Kosatsky 2010).

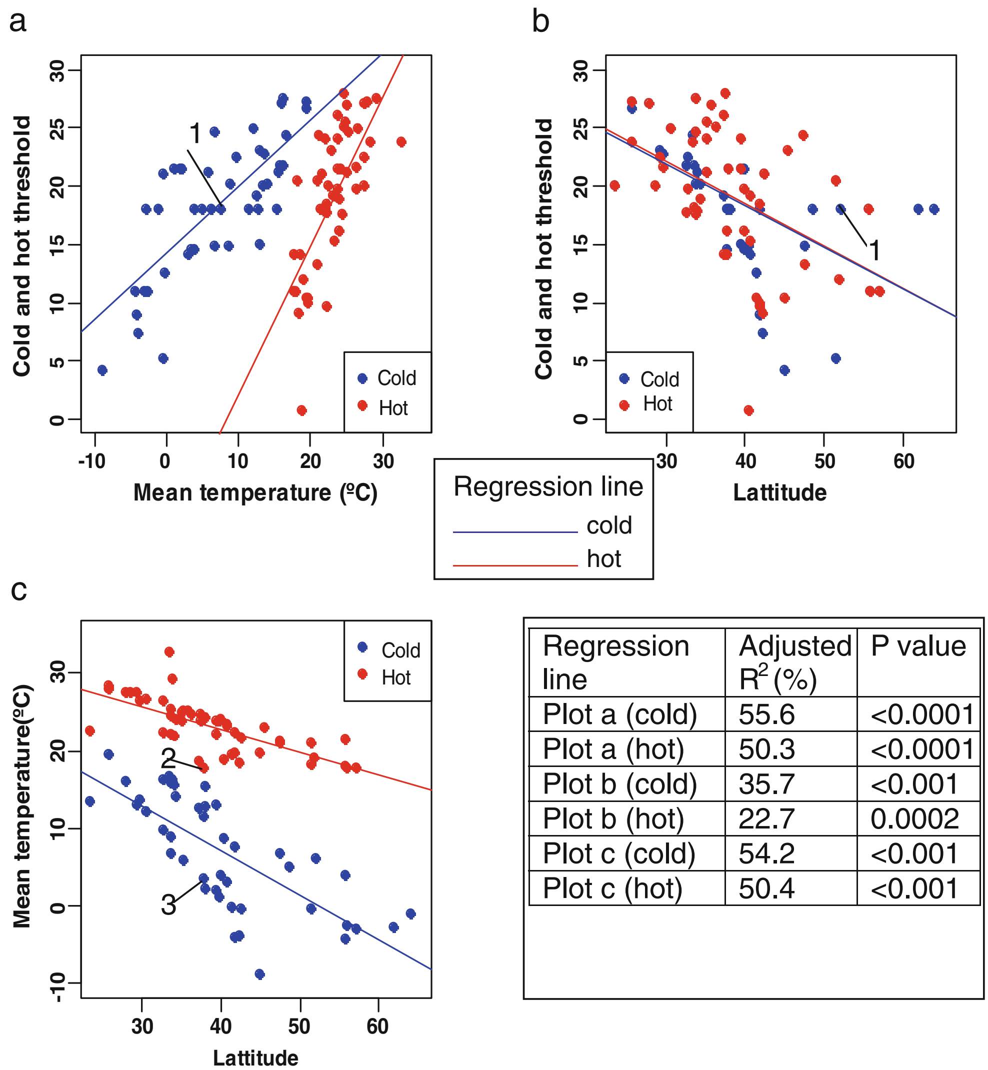
Strengths and limitations

The major strength of this meta-analysis is that we combined specific results in several temperature intervals. Previous meta-analyses identified threshold temperatures for all selected regions using several methods: choosing a certain percentile of temperature in each city (i.e., 99th percentile) (Medina-Ramón and Schwartz 2007); selecting an absolute temperature (i.e. 18°C) for all cities included (The Eurowinter Group 1997); or limiting the data to a single season (Analitis et al. 2008). None of these methods has resolved the complexity of threshold temperature in combining studies from various cities. However, these studies usually reported a high level of heterogeneity within the same territory or temperature band (Baccini et al. 2008; Medina-Ramón and Schwartz 2007).

The method applied in this study incorporated different thresholds for different cities, and also considered the effect estimates corresponding to various thresholds. We assumed less variability within a short temperature interval, and indeed the results suggest no substantial between-study variance in most temperature intervals.

We used daily mean temperature as exposure indicator for both heat and cold temperatures because (1) it may best reflect daily thermal stress and has been increasingly used in epidemiological studies (Anderson and Bell 2009; Hajat and Haines 2002; Kim et al. 2006); (2) average temperature experienced throughout the whole day and night usually provides more easily interpreted results within a policy context (Anderson and Bell 2009); (3) some researchers compared mean temperature with other indicators using statistical methods (e.g. comparison of AIC) and found that mean temperature was a better predictor of the death counts (Anderson and Bell 2009; Hajat and Haines 2002; Yu et al. 2010); and (4) we considered other temperature indicators in the preliminary literature review as different temperature

Fig. 4 The patterns of reported hot and cold thresholds, temperature and latitude



Regression line	Adjusted R^2 (%)	P value
Plot a (cold)	55.6	<0.0001
Plot a (hot)	50.3	<0.0001
Plot b (cold)	35.7	<0.001
Plot b (hot)	22.7	0.0002
Plot c (cold)	54.2	<0.001
Plot c (hot)	50.4	<0.001

Number	City	Latitude	Mean temperature (°C)
1	TheNetherlands	52.13	6.2
2	Palermo	38.12	15.4
3	Washington	38	2.22

indicators were used in different studies; however, very few studies would have been included in the meta-analysis if other indicators had been selected.

In addition, a number of important factors related to the design and implementation of the meta-analysis strategies were considered: (i) this meta-analysis involved 46 cities and almost 13 million deaths across diverse global climate zones, (ii) the elderly were selected as the target population to reduce heterogeneity across different locations due to their similar vulnerability, economic and living conditions; (iii) the eligibility criteria for the literature review were explicit and fairly stringent including the selection of a study population, study design, temperature indicators and endpoints; and (iv) Bayesian hierarchal models enabled the inclusion of different explanatory variables and the use of limited data to obtain more powerful conclusions (Girosi and King 2002).

However, several limitations should also be acknowledged. First, although we endeavoured to access all relevant studies from different sources, there is always the concern about publication bias in meta-analysis. Possible bias is evident in this study, as indicated by the funnel plot in Fig. 6, which depicts the reported percent increases in daily mortality by the corresponding precision of the estimates. The absence of relatively low estimates (below average) from small studies (with low precision) is apparent in the left hand tail of the figure. Second, the number of studies included in this analysis is limited and the quality of the overall assessment is

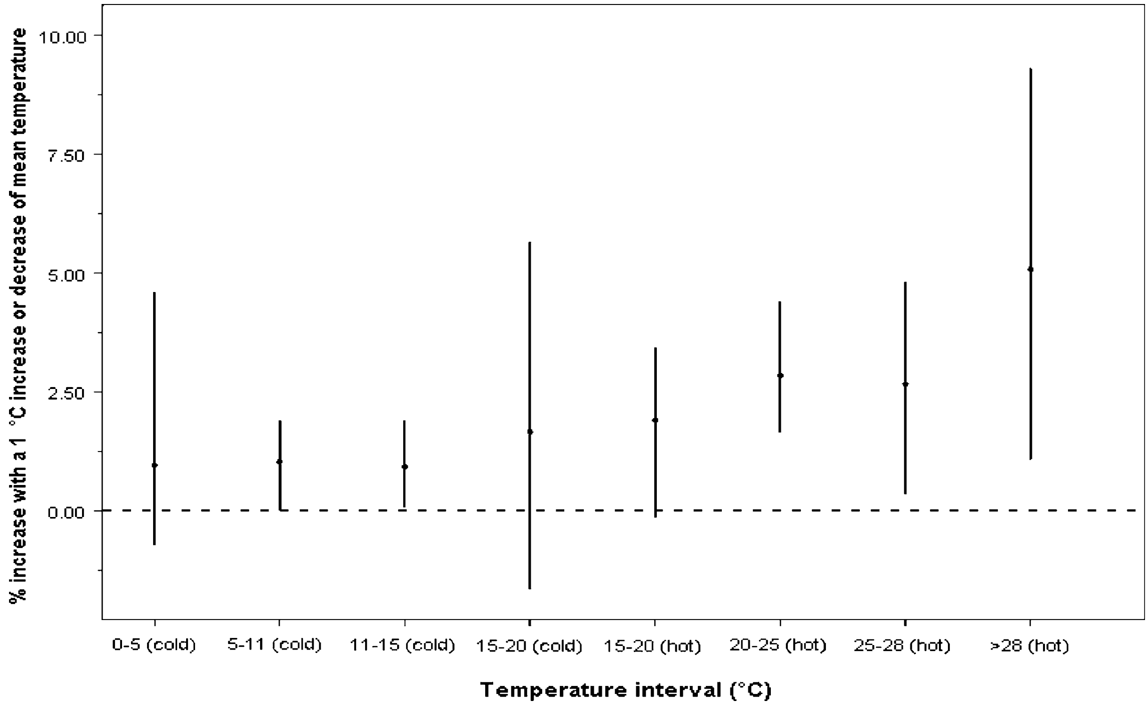


Fig. 5 Combined estimates of temperature variation on all-cause mortality among the elderly (mean and 95% posterior interval) based on a two-stage Bayesian hierarchical model for an exposure lag of 0 day

often dependent on the accuracy of the effect estimates from each selected investigation. We ameliorate these biases to some extent by weighing the study variance. Third, although we assessed the lagged effect in the two-stage Bayesian hierarchical model which may contribute to substantial ratios (within-study variance/between-study variance) in the temperature intervals of 11–15°C, 15–20°C (cold) and 15–20°C (hot), age- and sex-specific results may also result in the substantial ratios such as that observed in the temperature interval of 11–15°C (Donaldson and Keatinge 2003; Hajat et al. 2007; Ishigami et al. 2008). In practice, this may have affected the results for London, Budapest and Milan, but probably did not vary significantly as shown in Fig. 3. We did not find a substantial change in the overall conclusion when the articles by Donaldson and Keatinge (2003), Hajat et al. (2007) or Ishigami et al. (2008) were added or removed. Fourth, the included studies used different covariates although most studies controlled for day of week,

Table 2 Percent change in all-cause mortality among the elderly associated with a 1°C increase (or decrease) in seven temperature intervals[a]

No. of studies	Temperature interval (°C)	Posterior mean (ϑ_i) (95% CI)	Change with lag (a_k) (95% CI)	Variance between studies (ψ_b^2) (95% CI)	Ratio (variance within studies (τ_i^2)/ (ψ_b^2) (95% CI)
7 (cold)	0–5	0.96 (−0.72 to 4.60)	a_1: 0.27 (−0.20 to 0.51)	1.2E-4 (5.7E-4 to 39.6)	862.3 (1.1, 168.9)
8 (cold)	5–11	1.03 (0.02 to 1.91)	a1: 0.12 (0.01 to 0.24)[b]	4.5E-7 (5.1E-5 to 4.9)	329116.7 (10.7, 2076)
8 (cold)	11–15	0.92 (0.07 to 1.83)	a_1: 0.20 (−0.07 to 1.83) a_2: −0.004 (−0.02 to 0.01)	0.002 (2.5E-4 to 4.8)[b]	106.1 (11.0, 435.2)[b]
4 (cold)	15–20	1.66 (−1.64 to 5.65)	a_1: 0.02 (−0.15 to 0.23)	0.021 (0.017 to 60.5)[b]	2.1 (0.7, 8.9)[b]
5 (hot)	15–20	1.91 (−0.14 to 3.44)	a_1: 0.33 (−0.18 to 0.82)	3.1E-4 (4.7E-4 to 18.5)	5.7 (3.0, 133.9)[b]
9 (hot)	20–25	2.85 (1.65 to 4.41)	a_1:−0.16 (−0.62 to 0.21) a_2: 0.002 (−0.01 to 0.02)	0.006 (0.005 to 9.8)[b]	206.2 (5.9, 59.7)
7 (hot)	25–28	2.67 (0.36 to 4.81)	a_1: 0.56 (−0.93 to 2.88) a_2: −0.06 (−0.23 to 0.05)	5.6E-4 (0.004 to 24.6)	2527 (2.3, 152.4)
8 (hot)	>28	5.08 (1.07 to 9.32)	a_1: −0.13 (−0.37 to 0.06)	10.7 (3.2 to 84.0)[b]	0.6 (0.8, 0.9)

CI credible interval

[a] For an exposure lag of 0 day

[b] The 95% CI does not include zero

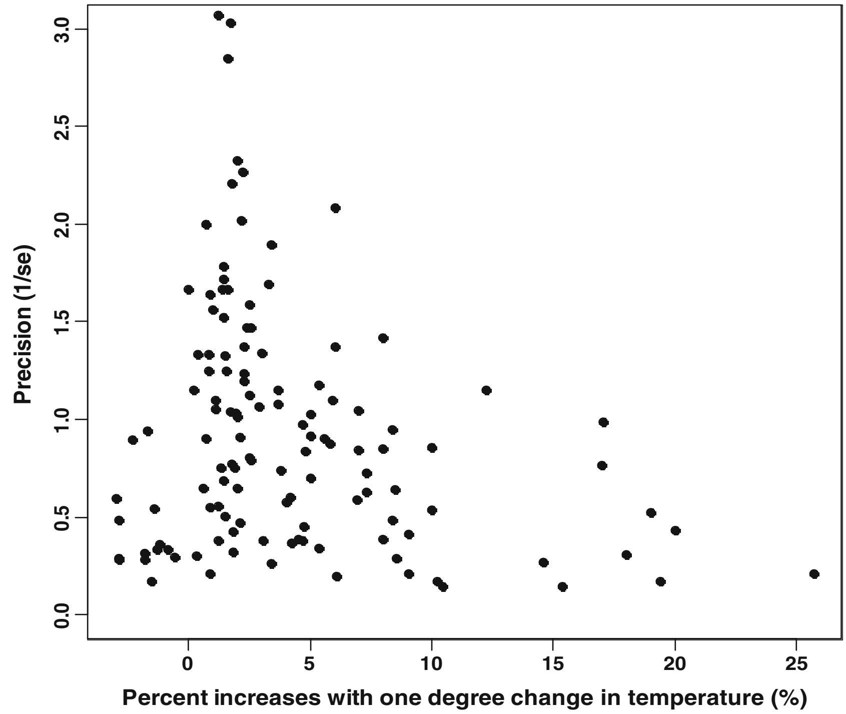


Fig. 6 Funnel plot of the reported percent increases by the corresponding precision of the estimates for the included studies

holidays, humidity, seasonality or time trend, which may contribute to heterogeneity of between-study variance within particular temperature intervals. Another issue was that the models used in this study do not allow for non-linear effects. To some extent, nonlinearities are encompassed by the lag effects and therefore the model can still provide valuable approximations. Finally, leaving out a great number of studies due to the use of different temperature variables is a problem. It may be desirable to use different indicators of temperature to verify the results of this meta-analysis. This work is warranted for future research.

Implications

Hot Weather–Health Watch/Warning Systems (HHWS) have been established in many cities throughout Europe and the United States (Ebi et al. 2004; Kovats and Ebi 2006). Prevention programmes that targeted the elderly and other high risk subgroups were activated in these cities based on the HHWS (Hajat et al. 2010). A series of studies have explored heat effects of weather on health in multiple cities and provided much information for public policy (Analitis et al. 2008; Anderson and Bell 2009; Medina-Ramón et al. 2006; Michelozzi et al. 2007). However, the challenge lies in determining at which point the weather conditions become sufficiently hazardous to human health to warrant intervention (Kovats and Hajat 2008). This meta-analysis provides apparent evidence that even a small change (i.e. 1°C) in average daily temperature will have an appreciable impact (2–5%) on elderly deaths in hot temperature intervals. In the meantime, this research may also provide additional information about cold-related deaths among the elderly since public health authorities appear to have paid less attention to this health hazard.

Future research

Several issues should be considered in future meta-analyses of temperature-related deaths, such as local climates, social-economic status, culture, demographics and living conditions. Further research is clearly needed to improve our understanding of the impact of temperature variation on elderly mortality within the context of environmental, social and behavioural changes.

Conclusions

This meta-analysis found that both hot and cold temperatures affected mortality in the elderly, but the magnitude of hot effects appeared to be stronger than that of cold effects, within a global context. Cold temperatures exhibited statistically substantial lagged effects, while hot temperatures did not.

Acknowledgments We thank Dr. Adrian Barnett and Dr. Lyle Turner at Queensland University of Technology for their statistical advice.

Competing interests We declare that we have no conflict of interest.

Funding This research was partly funded by the Australian Research Council (#559655) and Queensland University of Technology. S.T. was supported by an NHMRC Research Fellowship (# 553043), and W.Y. was supported by a Queensland University of Technology scholarship.

References

Analitis A, Katsouyanni K, Biggeri A, Baccini M, Forsberg B et al (2008) Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. Am J Epidemiol 168:1397–1408

Anderson BG, Bell ML (2009) Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiology 20:205–213

Armstrong B (2006) Models for the relationship between ambient temperature and daily mortality. Epidemiology 17:624–631

Baccini M, Biggeri A, Accetta G, Kosatsky T, Katsouyanni K et al (2008) Heat effects on mortality in 15 European cities. Epidemiology 19:711–719

Ballester F, Corella D, Perez-Hoyos S, Saez M, Hervas A (1997) Mortality as a function of temperature, a study in Valencia, Spain, 1991–1993. Int J Epidemiol 26:551–561

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ Health 8:40–52

Basu R, Dominici F, Samet JM (2005) Temperature and mortality among the elderly in the United States: a comparison of epidemiologic methods. Epidemiology 16:58–66

Bell ML, O'Neill MS, Ranjit N, Borja-Aburto VH, Cifuentes LA et al (2008) Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. Int J Epidemiol 37:796–804

Bouchama A, Knochel JP (2002) Heat stroke. N Engl J Med 346:1978–1988

Braga ALF, Zanobetti A, Schwartz J (2002) The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ Health Perspect 110:859–863

Carder M, McNamee R, Beverland I, Elton R, Cohen GR et al (2005) The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland. Occup Environ Med 62:702–710

Conti S, Masocco M, Meli P, Minelli G, Palummeri E, Solimini R, Toccacelia V, Vichia M (2007) General and specific mortality among the elderly during the 2003 heat wave in Genoa, Italy. Environ Res 103:267–274

Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA (2002) Temperature and mortality in 11 cities of the eastern United States. Am J Epidemiol 155:80–87

Donaldson GC, Keatinge WR (2003) Cold related mortality in England and Wales: influence of social class in working and retired age groups. J Epidemiol Community Health 57:790–791

Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF (2004) Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. Bull Am Meteor Soc 85:1067–1073

El-Zein A, Tewtel-Salem M, Nehme G (2004) A time-series analysis of mortality and air temperature in Greater Beirut. Sci Total Environ 330:71–80

Fouillet A, Rey G, Wagner V, Laaidi K, Empereur-Bissonnet P et al (2008) Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int J Epidemiol 37:309–317

Girosi F, King G (2002) Time series cross-sectional analysis with different explanatory variables in each cross-section. Center for Basic Research in the Social Sciences. Harvard University, Cambridge, pp 1–38

Goodman PG, Dockery DW, Clancy L (2004) Cause-specific mortality and the extended effects of particulate pollution and temperature exposure. Environ Health Perspect 112:179–185

Gouveia N, Hajat S, Armstrong B (2003) Socioeconomic differentials in the temperature-mortality relationship in Sao Paulo, Brazil. Int J Epidemiol 32:390–397

Hajat S, Haines A (2002) Associations of cold temperatures with GP consultations for respiratory and cardiovascular disease amongst the elderly in London. Int J Epidemiol 31:825–830

Hajat S, Kosatsky T (2010) Heat-related mortality: a review and exploration of heterogeneity. J Epidemiol Community Health 64:753–760

Hajat S, Kovats RS, Atkinson RW, Haines A (2002) Impact of hot temperatures on death in London: a time series approach. J Epidemiol Community Health 56:367–372

Hajat S, Armstrong BG, Gouveia N, Wilkinson P (2005) Mortality displacement of heat-related deaths—a comparison of Delhi, Sao Paulo, and London. Epidemiology 16:613–620

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? Occup Environ Med 64:93–100

Hajat S, O'Connor M, Kosatsky T (2010) Health effects of hot weather: from awareness of risk factors to effective health protection. Lancet 2010:856–863

Hastie TJ, Tibshirani RJ (1990) Generalized additive models. Chapman & Hall, New York

Ishigami A, Hajat S, Kovats RS, Bisanti L, Rognoni M et al (2008) An ecological time-series study of heat-related mortality in three European cities. Environ Health 7:5–11

Kaiser R, Le Tertre A, Schwartz J, Gotway CA, Daley WR et al (2007) The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. Am J Public Health 97: S158–S162

Kalkstein LS, Davis RE (1989) Weather and human mortality: an evaluation of demographic and interregional responses in the United States. Ann Assoc Am Geogr 79:44–64

Kan H, London SJ, Chen H, Song G, Chen G et al (2007) Diurnal temperature range and daily mortality in Shanghai, China. Environ Res 103:424–431

Kim Y, Joh S (2006) A vulnerability study of the low-income elderly in the context of high temperature and mortality in Seoul, Korea. Sci Total Environ 371:82–88

Kim H, Ha JS, Park J (2006) High temperature, heat index, and mortality in 6 major cities in South Korea. Arch Environ Occup Health 61:265–270

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Koppen-Geiger climate classification updated. Meteorol Z 15:259–264

Kovats RS, Ebi KL (2006) Heatwaves and public health in Europe. Eur J Public Health 16:592–599

Kovats R, Hajat S (2008) Heat stress and public health: a critical review. Annu Rev Public Health 29:22–37

Kysely J, Pokorna L, Kyncl J, Kriz B (2009) Excess cardiovascular mortality associated with cold spells in the Czech Republic. BMC Publ Health 9:19–29

Lorenzo F, Sharma V, Scully M, Kakkar V (1999) Cold adaptation and the seasonal distribution of acute myocardial infarction. Q J Med 92:747–751

McGeehin MA, Mirabelli M (2001) The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. Environ Health Perspect 109:185–189

McMichael AJ, Wilkinson P, Kovats RS, Pattenden S, Hajat S et al (2008) International study of temperature, heat and urban mortality: the 'ISOTHURM' project. Int J Epidemiol 37:1121–1131

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. Occup Environ Med 64:827–833

Medina-Ramón M, Zanobetti A, Cavanagh DP, Schwartz J (2006) Extreme temperatures and mortality: assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis. Environ Health Perspect 114:1331–1336

Michelozzi P, Fano V, Forastiere F, Barca A, Kalkstein LS et al (2000) Weather conditions and elderly mortality in Rome during summer. Bull World Met Org 49:348–355

Michelozzi P, De Sario M, Accetta G, de' Donato F, Kirchmayer U et al (2006) Temperature and summer mortality: geographical and temporal variations in four Italian cities. J Epidemiol Community Health 60:417–423

Michelozzi P, Kirchmayer U, Katsouyanni K, Biggeri A, McGregor G et al (2007) Assessment and prevention of acute health effects of weather conditions in Europe, the PHEWE project: background, objectives, design. Environ Health 6:12–21

Muggeo VM, Hajat S (2009) Modelling the non-linear multiple-lag effects of ambient temperature on mortality in Santiago and Palermo: a constrained segmented distributed lag approach. Br Med J 66:584–591

Nam IS, Mengersen K, Garthwaite P (2003) Multivariate meta-analysis. Stat Med 22:2309–2333

Pattenden S, Nikiforov B, Armstrong BG (2003) Mortality and temperature in Sofia and London. J Epidemiol Community Health 57:628–633

Revich B, Shaposhnikov D (2008) Temperature-induced excess mortality in Moscow, Russia. Int J Biometeorol 52:367–374

Rocklöv J, Forsberg B (2008) The effect of temperature on mortality in Stockholm 1998–2003: a study of lag structures and heatwave effects. Scand J Public Health 36:516–523

Spieghalter DJ, Thomas A, Best NG, Wilks WR (1995) Cambridge, BUGS: Bayesian using Gibbs sampling, version 5.0. MRC Biostatistics Unit, UK

Stafoggia M, Forastiere F, Agostini D, Caranci N, de' Donato F et al (2008) Factors affecting in-hospital heat-related mortality: a multi-city case-crossover analysis. J Epidemiol Community Health 62:209–215

Stafoggia M, Forastiere F, Michelozzi P, Perucci CA (2009) Summer temperature-related mortality: effect modification by previous winter mortality. Epidemiology 20:575–583

Stroup DF, Berlin JA, Morton SC, Olkin I, Williamson GD et al (2000) Meta-analysis of observational studies in epidemiology: a proposal for reporting. JAMA 283:2008–2012

The Eurowinter Group (1997) Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. The Eurowinter Group. Lancet 349:1341–1346

Tong S (2000) The potential impact of global environmental change on population health. Aust NZ J Med 30:618–625

World Bank (2001) GDP (per capita) (2001) by country. Available at: http://wwwnationmastercom/graph/eco_gdp_percap-economy-gdp-percapita&date=2001. Accessed on 25 May 2010

Yu W, Vaneckova P, Mengersen K, Pan X, Tong S (2010) Is the association between temperature and mortality modified by age, gender and socio-economic status? Sci Total Environ 408:3513–3518