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Review article

Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis

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ABSTRACT

Heatwave effects on human health and wellbeing is a great public health concern, especially in the context of climate change. However, no universally consistent heatwave definition is available. A systematic review and meta-analysis was conducted to assess the heatwave definitions used in the literature published up to 1st April 2015 by searching five databases (PubMed, ProQuest, ScienceDirect, Scopus, and Web of Science). Random-effects models were used to pool the effects of heatwave on total and cardiorespiratory mortality by different heatwave definitions. Existing evidence suggests a significant impact of heatwave on mortality, but the magnitude of the effect estimates varies under different heatwave definitions. Heatwave-related mortality risks increased by 4% (using "mean temperatures ≥95th percentile for ≥2 days" as a heatwave definition), 3% (mean temperatures ≥98th percentile for ≥2 days), 7% (mean temperatures ≥99th percentile for ≥2 days) and 16% (mean temperatures ≥97th percentile for ≥5 days). Heatwave intensity plays a relatively more important role than duration in determining heatwave-related deaths. Heatwaves significantly increase mortality across the globe, but the effect estimates vary with the definition of heatwaves. City- or region-specific heat health early warning systems based on identified local heatwave definitions may be optimal for protecting and preventing people from the adverse impacts of future heatwaves.

Contents

Abbreviations: CI, confidence interval; OR, odds ratio; RR, relative risk.

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1. Introduction

Heat is a well-recognized public health hazard (Basu and Samet, 2002; Basu, 2009; Ye et al., 2012). When exposed to heat, the thermoregulation system of human responds to offset the adverse effect of heat. However, once the heat is beyond certain limits, the risk of disease and death increases substantially on the day of exposure or few days after. The health impacts of sustained extreme heat, i.e., heatwaves, have been extensively researched (Kovats et al., 2004; Anderson and Bell, 2009, 2011; D'Ippoliti et al., 2010; Tong et al., 2014b), with some population groups, such as elderly people (D'Ippoliti et al., 2010; Son et al., 2012) and people living in urban areas (Conti et al., 2005; Madrigano et al., 2015), being reported to be particularly vulnerable to heatwave effects. It is projected that the intensity, frequency, duration, and geographic extent of heatwaves will increase as climate change progresses (Meehl and Tebaldi, 2004). Heatwaves will be very likely to pose a greater threat to human health and wellbeing as the world population is ageing (Lutz et al., 2008) and the pace of urbanization is accelerating at the global scale (McMichael, 2013), although heterogeneity in heatwave impact on mortality across different regions may exist (Benmarhnia et al., 2014; Vardoulakis et al., 2014).

Even though a heatwave is generally considered as a meteorological event, it should not be assessed without reference to its human health impacts (Robinson, 2001). Given this fact, it is very hard to reach a widespread consensus on how to define a heatwave as population acclimatization and adaptation is diverse across different regions. Prior research quantifying the health effects of heatwaves used various definitions of a heatwave, most of which adopted a combination of intensity and duration of heat to define a heatwave (Hajat et al., 2006; Anderson and Bell, 2009; Ma et al., 2015). Some studies compared the health impacts of heatwaves (or conducted sensitivity analysis) using different heatwave definitions, and found that even a slight change in the heatwave definition had an apparent effect on the estimated health impacts (Anderson and Bell, 2009; Tong et al., 2010b; Kent et al., 2015). These findings suggest that it is not appropriate to directly compare the findings of different studies assessing the health impacts of heatwaves if they are using different heatwave definitions.

Although the development of an internationally consistent heatwave definition may be unachievable, it is possible to develop an appropriate heatwave definition at a local or regional level. Several efforts have been made so far in Brisbane, Australia, and several mega-cities of China (Tong et al., 2014a; Gao et al., 2015). It is important to have a comprehensive understanding of heatwave definitions used in previous studies for the development of the guidelines to define an appropriate and consistent definition and to facilitate a comparison across different studies. In this paper, we systematically reviewed existing epidemiological evidence concerning the impacts of heatwaves on mortality, evaluated different heatwave definitions used in the existing literature, and pooled the mortality risks associated with heatwaves under various heatwave definitions.

2. Materials and methods

2.1. Data sources

Databases including PubMed, ProQuest, ScienceDirect, Scopus, and Web of Science were used to retrieve papers published between 1st January 2000 and 1st April 2015 regarding heatwaves and mortality. We manually checked the references of the identified papers to make sure all relevant papers were included.

2.2. Inclusion criteria

We used the following U.S. National Library of Medicine's Medical Subject Headings (MeSH terms) and keywords in the primary search: "climate change", "temperature", "heat wave", "heatwave", "death" and "mortality". Eligibility included any empirical studies written in English which used original data and appropriate effect estimates (e.g., relative risk (RR), odds ratio (OR), percentage change in mortality or excess mortality following heatwaves); where there was a clear definition of heatwave and heatwave was a main exposure of interest; and where all-cause mortality was analysed as a major outcome. For those studies using the same dataset and statistical approaches, we chose only one of them in the review. For example, Anderson et al. (Anderson and Bell, 2009) and Barnett et al. (Barnett et al., 2012) used the same US dataset, and we excluded the study of Barnett et al. in the review.

2.3. Meta-analysis

Mortality risks associated with heatwave, including total, cardiovascular, and respiratory mortality, were extracted from the identified papers. For those subgroups with two or more studies using the same heatwave definition, we pooled the relative risks (RRs) using meta-analysis (Table 1). Several studies were excluded from the meta-analysis either because they examined the main (i.e., the independent effects of daily ambient temperature) and added (i.e., the effect of persistent periods of heat) effects of heatwaves (Gasparrini and Armstrong, 2011; Zeng et al., 2014), or because the effect estimates it supplied were not suitable to be pooled (Williams et al., 2012). We also did not pool the added effect of heatwaves on mortality as the studies used different heatwave definitions (Gasparrini and Armstrong, 2011; Zeng et al., 2014). Another two studies (Chen et al., 2015; Kent et al., 2015) were excluded from the analysis because the temperature intensity metric they used were different from others. For example, other studies used mean temperature ≥95th percentile, while these two studies used >95th percentile. The RRs of two studies using the same heatwave definitions were not quantitatively combined as they used the same data but focused on different age groups (Tong et al., 2010a; Wang et al., 2012). Random-effects models were mainly used for the meta-analysis, and fixed-effects models were only used when no heterogeneity was detected. Heterogeneity was assessed by Cochran Q ($P < 0.10$ was considered statistically significant) and Higgins I^2 statistics ($I^2 > 40\%$ and $I^2 > 75\%$ were considered to indicate moderate and high heterogeneity, respectively). STATA version 12.0 (StataCorp, College Station, TX) was used to conduct the meta-analysis.

3. Results

3.1. Descriptive characteristics of identified studies

1608 papers were identified in the initial search. According to the inclusion criteria, 60 studies were included in the final review (Fig. 1). Among the 60 studies, 32 were conducted in Europe (Huynen et al., 2001; Hajat et al., 2002,2006; Kovats et al., 2004,2006; Vandentorren et al., 2004; Conti et al., 2005,2007; Dear et al., 2005; Grize et al., 2005; Johnson et al., 2005; Michelozzi et al., 2005; Nogueira et al., 2005; Pirard et al., 2005; Simón et al., 2005; Borrell et al., 2006; Le Tertre et al., 2006; Hutter et al., 2007; Rey et al., 2007; Fouillet et al., 2008; Revich and Shaposhnikov, 2008; Hertel et al., 2009; Schifano et al., 2009; D'Ippoliti et al., 2010; Basagaña et al., 2011; Green et al., 2012; Laaidi et al., 2012; Xu et al., 2013; Analitis et al., 2014; Miron et al., 2015; Rocklöv et al., 2014; Astrom et al., 2015), nine in the US (Kaiser et al., 2007; Yip et al., 2008; Anderson and Bell, 2009,2011; Ostro et al., 2009; Gasparrini and Armstrong, 2011; Kent et al., 2015; Zhang et al., 2015), eight in Australia (Tong et al., 2010a,2010b; Nitschke et al., 2011; Schaffer et al., 2012; Wang et al., 2012; Williams et al., 2012; Tong et al., 2014a,2014b), seven in China (Huang et al., 2010; Lan et al., 2012; Yang et al., 2013; Sun et al., 2014; Zeng et al.,

Table 1
Heatwave definitions used in the existing literature (maximum temperature, mean temperature and specific heatwave events).

Heatwave definitions used in the existing literature (maximum temperature)

Duration	Intensity	Heatwave criteria	Studies	Relative risk (RR) (95% CI)
2	35 °C	Maximum temperatures ≥35 °C for ≥2 days	Tong et al. (2010b) Wang et al. (2012)	Tong: 1.26 (1.10, 1.43) Wang: 1.46 (1.21, 1.77)
2	37 °C	Maximum temperatures ≥37 °C for ≥2 days	Tong et al. (2010b)	1.53 (1.27, 1.84)
2	97.5th	Maximum temperatures ≥97.5th percentile of the warm season for ≥2 days	Tong et al. (2010b)	1.16 (1.06, 1.27)
3	95th	Maximum temperatures ≥95th percentile for ≥3 days	Xu et al. (2013) Tong et al. (2010b)	Pooled RR: 1.20 (1.02, 1.41)
3	95th (warm season)	Maximum temperatures ≥95th percentile of the warm season for ≥3 days	Basagaña et al. (2011)	1.19 (1.17, 1.22)
3	97.5th	Maximum temperatures ≥97.5th percentile for ≥3 days	Tong et al. (2010b)	1.21 (1.08, 1.35)
3	98th	Maximum temperatures ≥98th percentile for ≥3 days	Lan et al. (2012)	1.41 (1.22, 1.63)
3	30 °C	Maximum temperatures ≥30 °C for ≥3 days	Hutter et al. (2007)	1.13 (1.09, 1.17)
3	32 °C	Maximum temperatures ≥32 °C for ≥3 days	Hertel et al. (2009)	1.28 (1.06, 1.53)
3	35 °C	Maximum temperatures ≥35 °C for ≥3 days	Huang et al. (2010), Nitschke et al. (2011), Sun et al. (2014), Tong et al. (2010b), Williams et al. (2012)[a]	Pooled RR: 1.08 (1.02, 1.13)
4	95th	Maximum temperatures ≥95th percentile for ≥4 days	Tong et al. (2010b)	1.14 (1.05, 1.24)
5	95th	Maximum temperatures ≥95th percentile for ≥5 days	Tong et al. (2010b)	1.24 (1.13, 1.36)
5	25 °C	Maximum temperatures ≥25 °C for ≥5 days, or maximum temperature ≥ 30 °C for ≥3 days	Huynen et al. (2001)	1.21
5	Exceeding the average maximum temperature by 5 °C	Maximum temperature exceeds the average maximum temperature by 5 °C for 5 consecutive days	Tong et al. (2010b)	0.99 (0.83, 1.18)
6	30 °C	Maximum temperature > 30 °C for 6 days	Kovats et al. (2004)	1.11 (1.03, 1.19)

Heatwave definitions used in the existing literature (mean temperature)

Duration	Intensity	Heatwave criteria	Studies	RR (95% CI)
2	90th, 95th–99th (warm season)	Mean temperatures ≥90th percentile for ≥2 days	Tong et al. (2014a,2014b)	A series of RRs under different lags
2	95th	Mean temperatures ≥95th percentile for ≥2 days	Anderson and Bell (2011), Ma et al. (2015), Zeng et al. (2014)[a], Zhang et al. (2015)	Pooled RR: 1.04 (1.03, 1.06)
2	97th	Mean temperatures ≥97th percentile for ≥2 days	Gasparrini and Armstrong (2011), Zhang et al. (2015);	Gasparrini and Armstrong: 1.05 (1.03, 1.07) (main effect) Zhang: 1.06 (0.92, 1.23)
2	98th	Mean temperatures ≥98th percentile for ≥2 days	Anderson and Bell (2009), Gasparrini and Armstrong (2011)[a], Rocklöv et al. (2014); Son et al. (2012);	Pooled RR: 1.03 (1.02, 1.04)
2	99th	Mean temperatures ≥99th percentile for ≥2 days	Anderson and Bell (2009), Gasparrini and Armstrong (2011)[a], Hajat et al. (2006), Zhang et al. (2015)	Pooled RR: 1.07 (1.04, 1.10)
2	99.5th	Mean temperatures ≥99.5th percentile for ≥2 days	Anderson and Bell (2009)	1.06 (1.04, 1.08)
3	90th, 95th, 99th (warm season)	Mean temperatures ≥90th (95th or 99th) percentile for ≥3 days	Tong et al. (2014a)	A series of RRs under different lags
4	90th, 95th, 99th (warm season)	Mean temperatures ≥90th (95th or 99th) percentile for ≥4 days	Tong et al. (2014a)	A series of RRs under different lags
4	97th	Mean temperatures ≥97th percentile for ≥4 days	Gasparrini and Armstrong (2011)	1.05 (1.04, 1.07) (main effect)
4	98th	Mean temperatures ≥98th percentile for ≥4 days	Anderson and Bell (2009); Gasparrini and Armstrong (2011)	Anderson and Bell: 1.04 (1.02, 1.06) Gasparrini and Armstrong: 1.06 (1.05, 1.08) (main effect)
4	99th	Mean temperatures ≥99th percentile for ≥4 days	Anderson and Bell (2009), Gasparrini and Armstrong (2011)	Anderson and Bell: 1.07 (1.03, 1.11) Gasparrini and Armstrong: 1.08 (1.05, 1.10) (main effect)
4	99.5th	Mean temperatures ≥99.5th percentile for ≥4 days	Anderson and Bell (2009)	1.06 (1.04, 1.08)
5	97th	Mean temperatures ≥97th percentile for ≥5 days	Hajat et al. (2002), Revich and Shaposhnikov (2008)	Pooled RR: 1.16 (0.91, 1.50)

Heatwave definitions used in the existing literature (specific heatwave events)

Heatwave criteria	Studies	Effect estimates
2010 Ahmedabad heatwave	Azhar et al. (2014)	1.76 (1.67, 1.83)/2.12 (2.03, 2.21)
2003 European heatwave	Borrell et al. (2006), Vandentorren et al. (2004)	Borrell: a series of RRs Vandentorren: a series of excess mortality in 13 cities
4 to 13 August 2003 European heatwave	Johnson et al. (2005), Kovats et al. (2006)	Johnson: 17% excess deaths Kovats: 1.13 (1.09, 1.18)/1.33 (1.30, 1.37)
1 to 13 August 2003 European heatwave	Laaidi et al. (2012)	2.17 (1.14, 4.16) (for a 0.41 °C increase in minimum temperature)

(continued on next page)

Table 1 (*continued*)

Heatwave definitions used in the existing literature (specific heatwave events)

Heatwave criteria	Studies	Effect estimates
1 to 14 August 2003 European heatwave	Dear et al. (2005)	A series of excess deaths for 12 cities
30 July to 15 August 2003 European heatwave	Nogueira et al. (2005)	1.38 (1.29, 1.48)/0.35 (0.26, 0.45)/0.36 (0.28, 0.46)
1 to 19 August 2003 European heatwave	Pirard et al. (2005)	More than 14,800 heat-related deaths in France, excess death rate ranged from 4% to 142% across regions
43-day period centered on 12 August 2003 European heatwave	Le Tertre et al. (2006)	RR ranged from 1.16 (0.93, 1.44) in Le Havre to 5.00 (4.62, 5.40) in Paris
16 June–31 August 2003 European heatwave	Conti et al. (2007)	For different heatwaves, RRs were different, ranging from 1.00 (0.87, 1.13) to 1.95 (1.77, 2.14)
1 June–31 August 2003 European heatwave	Conti et al. (2005), Grize et al. (2005), Michelozzi et al. (2005); Simón et al. (2005)	Conti: 3134 (excess deaths) Grize: 7% (excess mortality rate) Michelozzi: excess mortality rate ranged from 14% in Bologa to 33% in Turin Simon: 8% (excess mortality rate)
11 to 28 July 2006 French heatwave	Fouillet et al. (2008)	2065 excess deaths
2011 UK heatwave	Green et al. (2012)	367 excess deaths
1995 Chicago heatwave	Kaiser et al. (2007)	692 excess deaths
2006 California heatwave	Ostro et al. (2009)	A 9% (1.6, 16.3) increase in daily mortality per 10 Fahrenheit change in apparent temperature
2011 Sydney heatwave	Schaffer et al. (2012)	1.13 (1.06, 1.22)
7–26 February 2004 Brisbane heatwave	Tong et al. (2010b)	75 excess deaths

Heatwave definitions used in the existing literature (continued)

Temperature metric	Heatwave criteria	Studies	Effect estimates
Apparent temperature or heat index	Periods of at least two days with maximum apparent temperature exceeding the 90th percentile of the monthly distribution, or periods of at least two days in which minimum temperature exceeds the 90th percentile and maximum apparent temperature exceeds the median monthly value	D'Ippoliti et al. (2010)	Excess death rate ranged from 7.6% in Munich to 33.6% in Milan
	Maximum apparent temperatures > monthly threshold for ≥3 days	Schifano et al. (2009)	1.08 (1.02, 1.16) in 65–74 years and 1.15 (1.11, 1.18) in 75 + years
	Heat index ≥37.8 °C for ≥3 days	Yip et al. (2008)	57% (excess death rate)
	Maximum apparent temperatures ≥90th percentile for ≥2 days	Astrom et al. (2015)	Excess death rate ranged from 8% (3%, 12%) in Stockholm to 22% (18%, 26%) in Rome
Multiple indicators	Maximum temperatures >35.0 °C and mean temperature >98th percentile for ≥7 days	Yang et al. (2013)	1.23 (1.11, 1.37)
	The heat index is expected to reach 40.6 °C with a minimum temperature not below 26.7 °C as a period of at least 48 h	Tong et al. (2010a)	1.73 (1.32, 2.28)
	Maximum temperatures ≥90th percentile for ≥3 days; Minimum temperatures ≥90th percentile for ≥3 days and maximum temperature exceeding monthly mean temperature + 5	Ahmadnezhad et al. (2013)	1.03 (1.01, 1.05)
	A period of at least 2 days with maximum apparent temperature exceeding the 90th percentile of the monthly city-specific distribution or a period of at least 2 days in which minimum temperature exceeds the 90th percentile of the minimum monthly distribution and maximum apparent temperature exceeds the median monthly value	Analitis et al. (2014)	Excess death rate was 9.7% (2.9%, 16.9%) on low ozone days and 14.6% (10.5%, 18.7%) on high ozone days
	Moving averages (over three days) of the minimum and maximum temperatures of the HRs were equal to or exceeded certain predefined thresholds	Bustinza et al. (2013)	33% increase in mortality rate
	Periods of at least 3 consecutive days when the maximum and the minimum temperature, averaged over the whole France, were simultaneously greater than their respective 95th percentile	Rey et al. (2007)	Excess mortality rate ranged from 17% to 78% across different years
	15 heatwave definitions using mean temperature or maximum temperature as the temperature indicator, with different intensities and durations	Kent et al. (2015), Chen et al. (2015)	A series of RR estimates

[a] Study not included in the meta-analysis.

2014; Chen et al., 2015; Ma et al., 2015), one in Korea (Son et al., 2012), one in Iran (Ahmadnezhad et al., 2013), one in India (Azhar et al., 2014), and one in Canada (Bustinza et al., 2013). Table 2 shows the descriptive information on these studies.

3.2. Heatwave definitions

In general, the different heatwave definitions differ in three respects: 1) temperature metric; 2) intensity (i.e., temperature

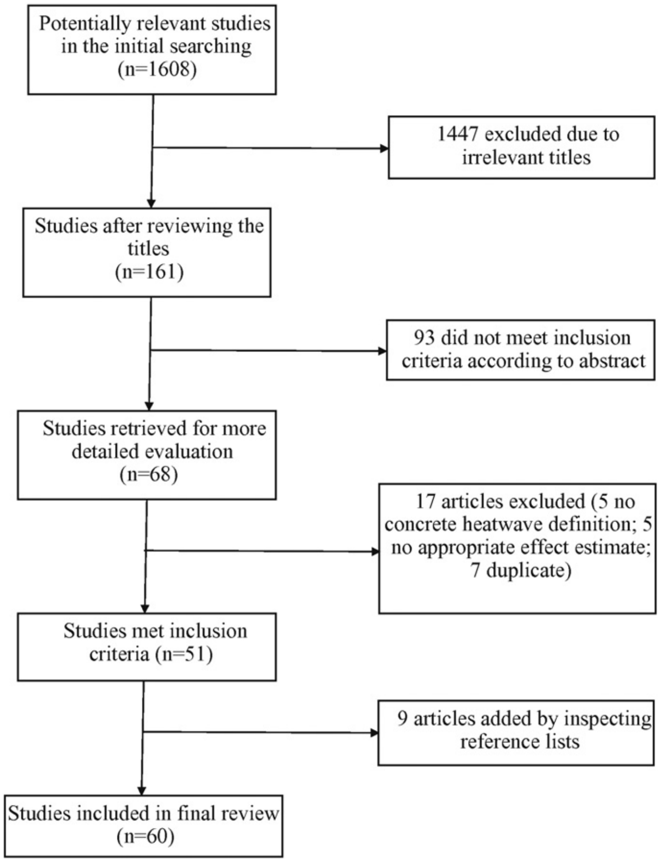


Fig. 1. The flow chart of literature selection process.

threshold); and 3) duration. For some record-breaking heatwaves (e.g., the 2003 European heatwave or the 1995 Chicago heatwave, etc.), researchers did not specify the temperature indicator, intensity or duration, but directly used the heat episode in the analysis to compare the mortality risk during the heatwave days with non-heatwave days (Vandentorren et al., 2004; Borrell et al., 2006; Ostro et al., 2009; Green et al., 2012; Schaffer et al., 2012). Table 1 presents the information on the specifics of heatwave definitions used in previous studies.

3.2.1. Temperature indicators

A range of temperature indicators, including maximum temperature, mean temperature, apparent temperature and heat index, have been used to define a heatwave in the literature. Some studies combined maximum (apparent) temperature with minimum temperature (Rey et al., 2007; D'Ippoliti et al., 2010; Ahmadnezhad et al., 2013; Bustinza et al., 2013; Analitis et al., 2014), or combined maximum temperature with mean temperature (Yang et al., 2013). Which temperature indicator performs the best in predicting mortality remains controversial. Some previous studies found that mean temperature was a better predictor of mortality than maximum and minimum temperature as it is more likely to represent the temperature level across 24 h (Hajat et al., 2006; Vaneckova et al., 2011; Chen et al., 2015). However, Laaidi et al. observed that, in elderly individuals, exposure to a high minimum temperature at night significantly increased the probability of death during a heatwave in urban areas, while daytime temperature was less important (Laaidi et al., 2012). Other have chosen apparent temperature or heat index because it combines temperature with humidity (Yip et al., 2008; Schifano et al., 2009; D'Ippoliti et al., 2010), which better approximates how temperature affects humans (Budd, 2008). Barnett et al. (Barnett et al., 2010) compared different temperature measures in 107 US cities and found the best temperature measure in terms of predicting mortality varied across cities, seasons and age groups, and no one temperature metric was superior to others. They suggested that, in the future studies, the criteria of choosing the best temperature measure can be based on practical concerns such as choosing the one with least missing data (Barnett et al., 2010).

3.2.2. Intensity

Two types of temperature threshold have been chosen to define a heatwave in previous studies, i.e., a relative threshold (temperature percentile) or an absolute threshold. Interestingly, a large proportion of prior studies using maximum temperature as the temperature indicator adopted an absolute temperature value as the threshold, and all studies using mean temperature as the temperature indicator adopted a relative threshold to define a heatwave (Table 1). Some studies using a relative threshold to define a heatwave assessed whether mortality risk increased with heatwave intensity by comparing the relative risks associated with different temperature thresholds (e.g., 90th, 95th, 99th, etc.). In 108 US cities, London (UK), Milan (Italy), Budapest (Hungary), and Brisbane (Australia), higher temperature threshold was found to be associated with greater heatwave effect on mortality (Hajat et al., 2006; Anderson and Bell, 2009; Tong et al., 2010b,2014a; Gasparrini and Armstrong, 2011). However, in four communities of Guangdong Province, China, and Houston, US, heatwave intensity did not significantly modify the heatwave effect on mortality (Zeng et al., 2014; Zhang et al., 2015).

3.2.3. Duration

Prior studies generally defined a heatwave as a heat episode with the duration over several days, ranging from one to seven days (Table 1). To better explore whether the duration of heatwave modifies the effect of heatwave on mortality, Hajat et al. proposed that the effect of heatwave on mortality can be attributed to the independent effects of daily ambient temperature (main effect) and of persistent periods (duration) of heat (added effect) (Hajat et al., 2006). Under this framework, some researchers assessed whether there was a significant heatwave added effect on mortality, and found significantly increased risks in 108 US cities (Anderson and Bell, 2009; Gasparrini and Armstrong, 2011), Essen (Germany) (Hertel et al., 2009), and Nanjing (China) (Chen et al., 2015). Further, Gasparrini and Armstrong also found that the added effect of heatwave on mortality increased with the increase in heatwave duration (Gasparrini and Armstrong, 2011). However, no significant differences were observed in the study of Zeng et al., which was conducted in four communities of Guangdong Province, China (Zeng et al., 2014). Compared with the main effect, the magnitude of the heatwave added effect was relatively smaller (Hajat et al., 2006; Gasparrini and Armstrong, 2011), implying that heatwave intensity, rather than duration, might be the major driver of heatwave-associated mortality (Anderson and Bell, 2011), although heterogeneity still exists across different communities (Rocklöv et al., 2011; Tong et al., 2014a).

3.2.4. Pooled effects of heatwave on mortality under different definitions

Effects of heatwave on mortality under six heatwave definitions were pooled in the meta-analysis (Fig. 2). Due to data availability issue, effects of heatwave on cardiovascular or respiratory diseases under only two heatwave definitions were quantitatively combined together (Fig. 3). Significant heterogeneity was observed across different studies, and thus we used random-effect models. Within the same study, heatwave effect on mortality normally increased while using heatwave definition of greater intensity or longer duration. However, across studies, we found that for those studies using the same duration (≥2 days) but different intensities (95th, 98th, or 99th percentile of mean temperature), heatwave effect on mortality did not show an appreciable increasing trend with the increase in intensity (RR: 1.04, 1.03 and 1.07, respectively) (Fig. 2b). Similarly, for those studies using the same heatwave intensity (e.g., 95th percentile of maximum

Table 2
Characteristics of included studies.

Authors and year of publication	Outcome investigated	Location and period of data obtained	Temperature measure(s)	Heatwave definition
Ahmadnezhad et al. (2013)	Total, CVD, RD, and CBD mortality	Tehran, Iran, warm season, 2001–2011	Daily mean, minimum, and maximum temperature	Maximum temperatures ≥90th percentile for ≥3 consecutive days; Minimum temperatures ≥90th percentile for ≥3 days and maximum temperature exceeding monthly mean temperature +5
Analitis et al. (2014)	Total, CVD, RD, and CBD mortality	9 European cities, Europe, 1990–2004	Daily mean, minimum, and maximum temperature	A period of at least 2 days with maximum apparent temperature exceeding the 90th percentile of the monthly city-specific distribution
Anderson and Bell (2009)	Total, CVD, RD and non-CVD or RD mortality	107 US communities, US, 1987–2000	Daily mean, minimum, and maximum temperature, and apparent temperature	Periods of 2 or more or 4 or more days of continuous temperatures more than 98.5th, 99th, or 99.5th percentile of the community's temperature distribution.
Anderson and Bell (2011)	Total mortality	43 US communities, US, Warm season, 1987–2005	Daily mean, minimum, and maximum temperature	Mean temperatures ≥95th percentile for ≥2 days
Azhar et al. (2014)	Total mortality	Ahmedabad, India, 2009–2011	Daily maximum temperature	2010 Ahmedabad heatwave
Basagaña et al. (2011)	Total mortality	Catalonia region, Spain, 1983–2006	Daily mean, minimum, and maximum temperature	Maximum temperatures ≥95th percentile of the warm season for ≥3 days
Borrell et al. (2006)	Total mortality	Barcelona, Spain, 1998–2003	Daily maximum temperature	2003 European heatwave
Bustinza et al. (2013)	Mortality, and EDAs	Quebec, Canada, 2010	Daily mean, minimum, and maximum temperature	Moving averages (over three days) of the minimum and maximum temperatures of the HRs were equal to or exceeded certain predefined thresholds
Chen et al. (2015)	Total, CVD, RD, Stroke, IHD and COPD mortality	Nanjing, China, 2007–2013	Daily mean and maximum temperature	Mean temperatures ≥98th percentile for ≥4 days
Conti et al. (2005)	Total mortality	21 capital cities of Italy, Italy, 2002–2003	Humidex Index	1 June–31 August 2003 European heatwave
Conti et al. (2007)	Total and cause-specific mortality	Genoa, Italy, 2002–2003	Daily maximum and minimum temperature, and Humidex Index	16 June–31 August 2003 European heatwave
Dear et al. (2005)	Total mortality	12 cities in France, 2003	Maximum, minimum and mean temperature	1 to 14 August 2003 European heatwave
D'Ippoliti et al. (2010)	Total mortality	9 European cities, 1990–2004	Daily apparent temperature	1) periods of at least two days with maximum apparent temperature exceeding the 90th percentile of the monthly distribution or 2) periods of at least two days in which minimum temperature exceeds the 90th percentile and maximum apparent temperature exceeds the median monthly value.
Fouillet et al. (2008)	Total mortality	France, 1975–2006	Daily mean, minimum, and maximum temperature	11 to 28 July, 2006 French heatwave
Gasparrini and Armstrong (2011)	Total mortality	108 US communities, US, 1987–2000	Daily mean, minimum, and maximum temperature	Mean temperatures ≥97th (98th or 99th) percentile for ≥2 (or 4) days
Green et al. (2012)	Total mortality	England and Wales, UK, 2011	Daily mean and maximum temperature	2011 UK heatwave
Grize et al. (2005)	Total mortality	Switzerland, 1990–2003	Daily mean, minimum, and maximum temperature	June to August 2003 European heatwave
Hajat et al. (2002)	Total mortality	Greater London, UK, 1976–1996	Daily mean, minimum, and maximum temperature	Mean temperatures ≥97th percentile for ≥5 days
Hajat et al. (2006)	Total, CVD, and RD mortality	London (England), 1976–2003; Budapest (Hungary), 1970–2000; and Milan (Italy), 1985–2002	Daily mean, minimum, and maximum temperature, and apparent temperature	Periods of 2 or more or 4 or more days of continuous temperatures more than 98.5th, 99th, or 99.5th percentile of the city's temperature distribution
Hertel et al. (2009)	Total, CVD, RD and neoplastic mortality	Essen, Germany, 2000–2006	Daily mean, minimum, and maximum temperature	Maximum temperatures ≥32 °C for ≥3 days
Huang et al. (2010)	Total, CVD, and RD mortality	Shanghai, China, 2003	Daily maximum temperature	Maximum temperatures ≥35 °C for ≥3 days
Hutter et al. (2007)	Total mortality	Vienna, Austria, 1998–2004	Daily maximum temperature	Maximum temperatures ≥30 °C for ≥3 days
Huynen et al. (2001)	Total, CVD, RD and neoplastic mortality	Netherlands, 1979–1997	Daily mean, minimum, and maximum temperature	A period of at least 5 days, each of which has a maximum temperature of at least 25 °C, including at least 3 days with a maximum temperature of at least 30 °C
Johnson et al. (2005)	Mortality, and EHAs	England, 2003	Daily mean, minimum, and maximum temperature	4 to 13 August 2003 European heatwave
Kaiser et al. (2007)	Total and cause-specific mortality	Chicago, US, 1995	Daily mean, minimum, and maximum temperature	1995 Chicago heatwave
Kent et al. (2015)	Mortality and preterm birth	Alabama, US, 1990–2010	Daily mean, minimum, and maximum temperature	15 definitions based on different duration and intensity
Kovats et al. (2004)	Mortality and HAs	Greater London, UK, 1994–2000	Daily mean, minimum, and maximum temperature	Maximum temperature > 30 °C for 6 days
Kovats et al. (2006)	Total mortality	South East, South West, East of	Daily mean, minimum, and	4 August and 13 August 2003 European

Table 2 (*continued*)

Authors and year of publication	Outcome investigated	Location and period of data obtained	Temperature measure(s)	Heatwave definition
		England, and London, UK, 1998–2003	maximum temperature	heatwave
Laaidi et al. (2012)	Total mortality	Paris, France, 2003	Daily mean, minimum, and maximum temperature	1 August and 13 August 2003 European heatwave
Lan et al. (2012)	Total mortality	Harbin, China, 2009–2011	Daily mean, minimum, and maximum temperature	Maximum temperatures ≥98th percentile for ≥3 days
Le Tertre et al. (2006)	Total mortality	9 French cities, France, 1996–2003	Daily mean, minimum, and maximum temperature	43-day period centered on 12 August 2003 European heatwave
Ma et al. (2015)	Total, CVD, RD, and CBD mortality	66 communities in China, China, 2006–2011	Daily mean, minimum, and maximum temperature	Heatwaves were defined as ≥2 consecutive days with mean temperature ≥95th percentile of the year-round community-specific distribution
Michelozzi et al. (2005)	Total mortality	4 Italian cities, Italy, 1995–2003	Maximum apparent temperature	June to August, 2003 European heatwave
Miron et al. (2015)	Total mortality	Spain, 1975–2008	Daily maximum temperature	Maximum temperature above a calculated threshold for more than one day
Nogueira et al. (2005)	Total and cause-specific mortality	Portugal, 2003	Daily maximum temperature	30 July to 15 August, 2003 European heatwave
Nitschke et al. (2011)	Mortality, HAs, EDPs, and ACOs	Adelaide, Australia, 1993–2009	Daily maximum temperature	Maximum temperatures ≥35 °C for ≥3 days
Ostro et al. (2009)	Total mortality	Seven counties in California, US, 2006	Daily apparent temperature	2006 California heatwave
Astrom et al. (2015)	Total mortality	Stockholm (Sweden) and Rome (Italy), 2000–2008	Daily mean, minimum, and maximum (apparent) temperature	Maximum apparent temperatures ≥90th percentile for ≥2 days
Pirard et al. (2005)	Total and cause-specific mortality	13 French cities, France, 1999–2003	Daily mean, minimum, and maximum temperature	1 to 19 August, 2003 European heatwave
Revich and Shaposhnikov (2008)	Total and CVD, RD and IHD mortality	Moscow, Russia, 2000–2006	Daily mean, minimum, and maximum temperature	Mean temperatures ≥97th percentile for ≥5 days (or Mean temperatures ≥99th percentile for ≥3 days)
Rey et al. (2007)	Total and cause-specific mortality	France, 1971–2003	Daily mean, minimum, and maximum temperature	Periods of at least three consecutive days when the maximum and the minimum temperature were simultaneously greater than their respective 95th percentile.
Rocklöv et al. (2014)	Total mortality	Stockholm county, Sweden, 1990–2002	Daily mean, minimum, and maximum temperature	Temperatures ≥98th percentile for ≥2 days
Schaffer et al. (2012)	Mortality, and EDVs	Sydney, Australia, 2011	Daily mean, minimum, and maximum temperature	2011 Sydney heatwave
Schifano et al. (2009)	Total mortality	Rome, Italy, 2005–2007	Daily maximum and apparent temperature	Maximum apparent temperatures > monthly threshold for ≥3 days
Simón et al. (2005)	Total mortality	Spain, 1980–2003	Daily mean, minimum, and maximum temperature	June to August, 2003 European heatwave
Son et al. (2012)	Total mortality	7 Korean cities, Korea, 2000–2007	Daily mean temperature	Mean temperatures ≥98th percentile for ≥2 days
Sun et al. (2014)	Total mortality	Pudong district, Shanghai, China, 2008–2013	Daily mean, minimum, and maximum temperature	Maximum temperatures ≥35 °C for ≥3 days
Tong et al. (2010b)	Total mortality	Brisbane, Australia, 2001–2004	Daily mean, minimum, and maximum temperature	7–26 February 2004 Brisbane heatwave
Tong et al. (2010a)	Mortality and EHAs	Brisbane, Australia, 1996–2005	Daily mean, minimum, and maximum temperature	Ten heatwave definitions based on duration and intensity
Tong et al. (2014a)	Mortality and EHAs	Brisbane, Australia, 1996–2005	Daily mean, minimum, and maximum temperature	A series of heatwave definitions
Tong et al. (2014b)	Total mortality	3 cities of Australia, Australia, 1988–2009	Daily mean, minimum, and maximum temperature	Mean temperature above a heat threshold for 2 or more consecutive days in the summer season
Vandentorren et al. (2004)	Total mortality	13 French cities, France, 1999–2003	Daily mean, minimum, and maximum temperature	2003 European heatwave
Wang et al. (2012)	Mortality and EHAs	Brisbane, Australia, 1996–2005	Daily maximum temperature	Maximum temperatures ≥37 °C for ≥2 days
Williams et al. (2012)	Mortality, HAs, EDPs	Perth, Australia, 1980–2008	Daily maximum temperature	Maximum temperatures ≥35 °C for ≥3 days
Xu et al. (2013)	Total mortality	Barcelona, Spain, 1999–2006	Daily maximum temperature	Maximum temperatures ≥95th percentile of the warm season for ≥3 days
Yang et al. (2013)	Total mortality	Guangzhou, China, 2003–2006	Daily mean, minimum, and maximum temperature	Maximum temperatures >35.0 °C and mean temperature >98th percentile for ≥7 days
Yip et al. (2008)	Total mortality	Maricopa County, US, 2000–2005	Daily mean, minimum, and maximum temperature	Heat index ≥37.8 °C for ≥3 days
Zeng et al. (2014)	Total mortality	Four cities, China, 2006–2010	Daily mean, minimum, and maximum temperature	Mean temperatures ≥95th percentile for ≥2 days
Zhang et al. (2015)	Mortality and EDVs	Houston, US, 2007–2011	Daily mean, minimum, and maximum temperature	2 to 30 August, 2011 Sydney heatwave, and another three definitions

ACOs, ambulance call-outs; CBD, cerebrovascular diseases; COPD, chronic obstructive pulmonary disease; CVD, cardiovascular diseases; EDA, emergency department admission; EDPs, emergency department presentations; EDVs, emergency department visits; HAs, hospital admissions; IHD, ischemic heart disease; RD, respiratory diseases.

temperature) but different durations (e.g., 3, 4 or 5 days), no apparent increasing trend in the heatwave effect on mortality was observed (RR: 1.20, 1.14 and 1.24, respectively) across the different studies (Table 1).

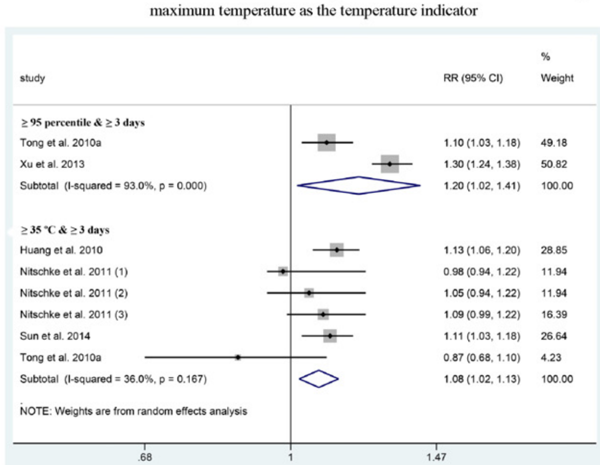
4. Discussion and recommendations

This is the first systematic review and meta-analysis of the effect of heatwaves on mortality under different heatwave definitions. Unsurprisingly, most studies reported a significant increase in mortality during heatwave days. Significant heterogeneity among studies in the meta-analysis was detected, which is attributable to several reasons. Firstly, different climates of the study sites may play an important role in driving the variability (Hajat and Kosatky, 2010). Secondly, the different study designs and statistical approaches used may contribute to the variability between studies. Finally, the different socio-demographic characteristics of the study populations may also result in heterogeneity.

Several notable findings regarding the key components of heatwave definition have been observed: 1) within the same region, mortality risk increased with increases in heatwave intensity/duration. However, across different regions, heatwave pooled effect on mortality did not show an appreciable increasing trend with the increase in intensity/duration; 2) heatwave intensity plays a more important role than duration in heatwave-related deaths; and 3) to date, no temperature indicator has been found to be superior to others for the assessment of heatwave-related mortality.

An appropriate heatwave threshold temperature is fundamentally important for the development of heatwave definitions and early warning systems. An extremely high threshold temperature (e.g., 99th percentile of maximum temperature) may result in the underestimation of heat-related deaths as mildly high temperature (e.g., 90th percentile of maximum temperature) may have already substantially increased mortality in some regions, and a too low threshold temperature may trigger heatwave early warning too early, wasting health resources (Tobias et al., 2012; Diaz et al., 2015). How to choose a desirable heatwave threshold temperature still remains controversial. Most researchers have used a meteorology-based criterion, or a given temperature percentile without providing the reasons for choosing one particular temperature metric over another (Kovats et al., 2004; Anderson and Bell, 2009; Hertel et al., 2009; Son et al., 2012). Some researchers have proposed that it is more appropriate to establish a local heatwave threshold temperature based on the relationship between heatwave and the health of a given population (i.e., a health-based metric) (Montero et al., 2010). As the ultimate goal of assessing health impacts of heatwaves is to develop targeted public health interventions to prevent and mitigate heatwave impacts, regional differences and local characteristics should be taken into account in the

a. Pooled effects of heatwaves on mortality under two heatwave definitions using maximum temperature as the temperature indicator



b. Pooled effects of heatwaves on mortality under four heatwave definitions using mean temperature as the temperature indicator

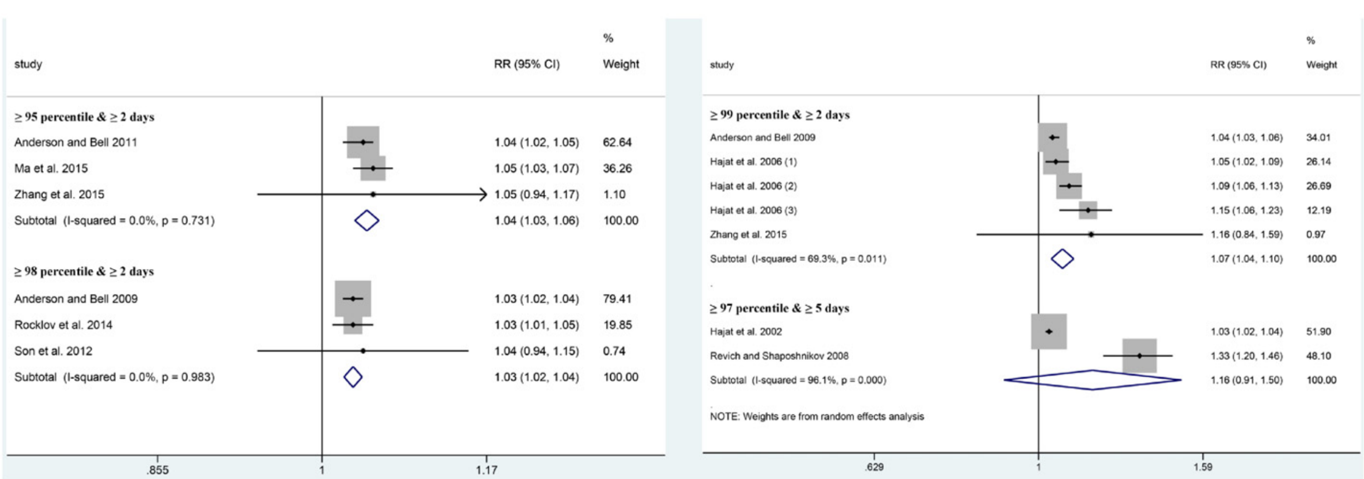


Fig. 2. a. Pooled effects of heatwaves on mortality under two heatwave definitions using maximum temperature as the temperature indicator. b. Pooled effects of heatwaves on mortality under four heatwave definitions using mean temperature as the temperature indicator.

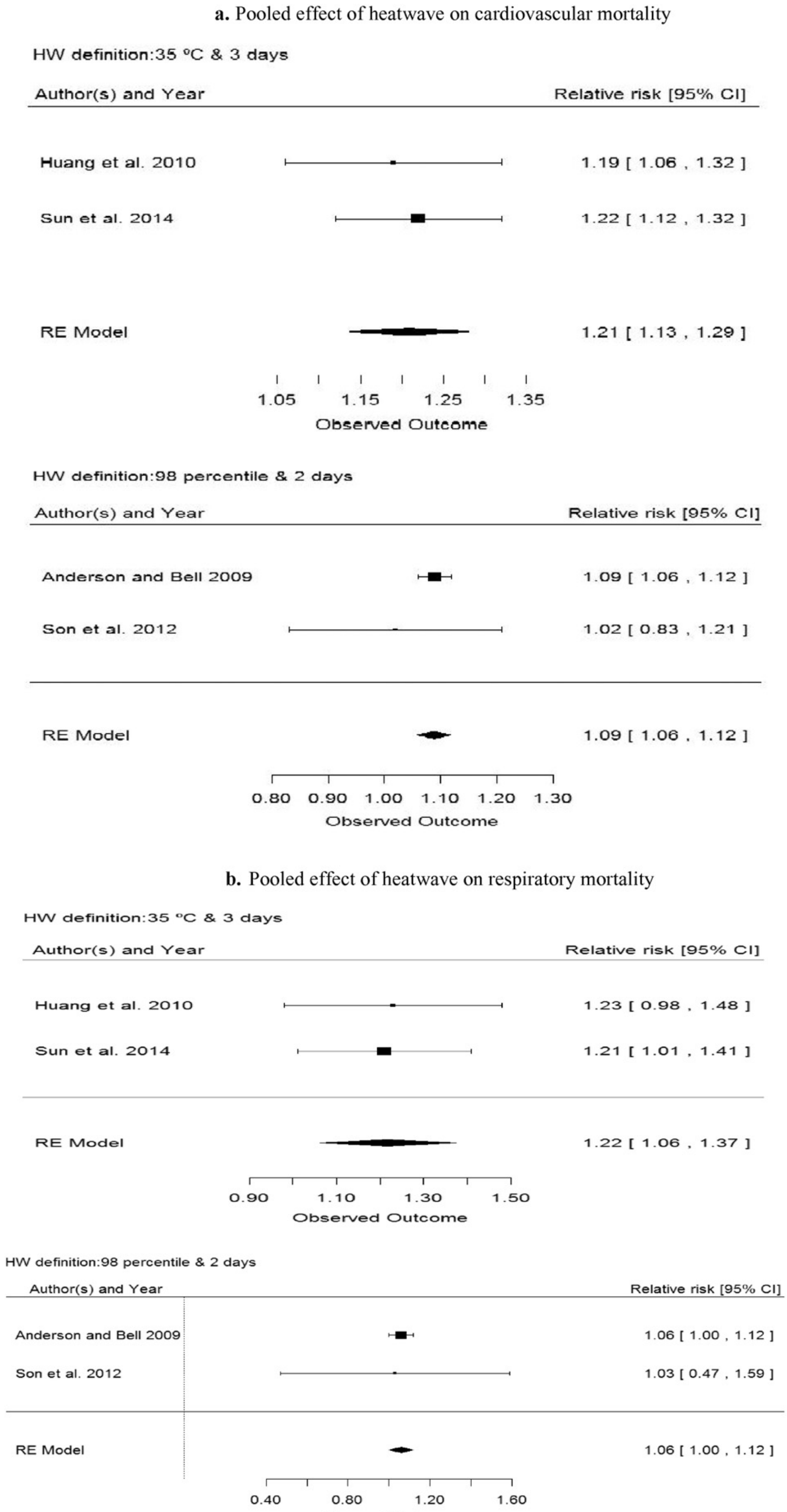


Fig. 3. a. Pooled effect of heatwave on cardiovascular mortality. b. Pooled effect of heatwave on respiratory mortality.

development of heatwave threshold temperature (Kim et al., 2006; Montero et al., 2012). Thus, a city-specific heatwave definition combining both meteorological and health perspectives will facilitate the development of appropriate heat health early warning systems and minimise heat-related deaths.

To identify the heatwave threshold temperature, researchers need to detect the temperature inflexion point at which mortality starts to substantially increase (Cunningham et al., 2013). Just like minimum-mortality-temperature percentile, the inflexion point temperature percentile may not be a widely used percentile (e.g., 95th percentile or 99th percentile) (Guo et al., 2014). As such, it is essential to conduct studies with great care and robustness to not just quantify the temperature-mortality relationship in specific region but also capture the characteristics which may affect this relationship. Further, the temperature-mortality relationship may also change over time (Davis et al., 2003; Guo et al., 2012; Miron et al., 2015), and thus it is necessary to check if the percentiles of the mortality firing temperatures have varied with the passage of time to complete the definition of a heat wave (Linares et al., 2014). For example, as the population of a region ages, the threshold temperature corresponding to the inflexion point may be lower and therefore the heatwave threshold temperature will also need to be adjusted with the passage of time.

Although there has been much effort to develop a framework in defining a heatwave, more still remains to be done. We have presented the knowledge gaps related to temperature intensity, heatwave duration and temperature indicator. Firstly, even though an international or national heatwave definition is not easy to develop, it is still possible to develop a local or regional heatwave definition. As such, large scale studies using robust statistical approaches to explore an appropriate heatwave threshold temperature in regions within the same climate zone or with similar demographic characteristics are needed. For example, health risk-based metrics are proposed to explore a suitable heatwave definition (Tong et al., 2014a). All prior studies quantifying heatwave effect on mortality used a given temperature percentile (e.g., 75th percentile) as the reference temperature. However, the minimum-mortality-temperature-percentile has been recently proposed as a better reference temperature indicator (Gasparrini et al., 2015; Guo et al., 2014).

Secondly, the duration of extreme heat exposure which significantly increases mortality risk varies across different regions (Gasparrini and Armstrong, 2011; Zeng et al., 2014). Researchers tend to use two or four days as the duration to define a heatwave without providing the reasons behind their choice. Although identifying a duration beyond which the added effect of persistent heat on mortality becomes significant may be helpful in choosing the appropriate heatwave duration statistically, it may not fully explain the complexity of heatwave effect on mortality as the main effect of heat and added effect of sustained heat may work independently or interactively to adversely affect health and wellbeing. Further studies are needed to develop a more evidence-based framework to choose an appropriate duration to define a heatwave.

Thirdly, optimal temperature indicators may vary across different cities and age groups. Most people may spend more time at home or at a cool place during heatwave days, implying that the roles of indoor temperature and outdoor temperature should be better elucidated. Further, exploration of the most sensitive temperature indicator for vulnerable people, especially the elderly, at a city or regional level, will largely facilitate the development of an appropriate heatwave definition.

In conclusion, this systematic review and meta-analysis suggests a significant adverse heatwave effect on mortality, but the magnitude of this effect varies with different heatwave definitions. Elderly, children, females and people with disadvantaged socioeconomic status or chronic diseases should be well protected during heatwave days. City- or region-specific heat health early warning systems based on the identified threshold temperature and significant heatwave duration may be optimal for protecting and preventing people from the adverse impacts of future heatwaves. International collaborations are urgently needed to properly address the health impacts of heatwaves so that the guidelines for better defining a heatwave can also be developed.

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Conflict of interest

No declared.

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