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# Heatwave and elderly mortality: An evaluation of death burden and health costs considering short-term mortality displacement

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ABSTRACT

*Background:* A heatwave can be a devastating natural disaster to human health, and elderly people are particularly vulnerable. With the continuing rise in earth's surface temperature alongside the world's aging population, research on the mortality burden of heatwave for the older population remains relatively sparse. The potential magnitude of benefits of averting such deaths may be considerable.
*Objectives:* This paper examined the short-term mortality displacement (or "harvesting") of heatwave, characterized the heatwave-mortality relationship, and estimated death burden and health costs attributable to heatwave among the elderly in Australia.
*Methods:* We collected daily data on the temperature and deaths of people aged ≥75 years in the five largest cities of Australia (Sydney, Melbourne, Brisbane, Perth and Adelaide), totaling 368,767 deaths in different periods between 1988 and 2011. A total of 15-tiered heatwave definitions, based on intensity (95th to 99th percentiles of temperature distribution) and duration (two or more consecutive days), were used to quantify heatwave effects, using time-series regression and random-effects meta-analysis. We calculated attributable deaths for each city and by different types of heatwave. Potential economic benefits in monetary terms were also estimated, considering that heat-related deaths are avoidable.
*Results:* Among the Australian elderly population, we found significant associations between heatwave and deaths, with raised mortality immediately in the first few days followed by lower-than-expected mortality. In general, heatwave was associated with an average death increase of 28% (95% confidence interval: 15% to 42%), and greater increases were mostly observed for more intense heatwaves across multiple megacities. During the study period, there were dozens to hundreds of deaths attributable to heatwave for each city, equating to an economic loss of several million Australian dollars every year. Although the estimated attributable deaths varied by heatwave intensity and duration, the pattern was not consistent across cities.
*Conclusions:* Heatwave caused harvesting effects on mortality in the elderly population of Australia, and contributed to a substantial amount of death burden and indirect financial costs. To lessen the health impacts of heatwave in the affected regions, effective heatwave early warning systems and interventions targeted at the elderly population could be beneficial, both now and in the future.

## 1. Introduction

Heatwaves have adverse impacts on human health and well-being historically, making it one of the most hazardous natural disasters in many regions of the world (Coates et al., 2014; Mora et al., 2017; Forzieri et al., 2017). The well-known 2003 European heatwave is a vivid example that the resulting death toll reached over 70, 000 (Robine et al., 2008). A series of lethal heatwaves has been recorded worldwide, and ongoing climate change will cause more intense, more frequent and longer-lasting heatwaves in the 21st century (Mora et al., 2017; Xu et al., 2016; Meehl and Tebaldi, 2004). Preventing the adverse health consequences of hot weather is now an important subject for public health locally, regionally and globally (Hajat et al., 2010; Guo et al., 2017). Meanwhile, aged people are particularly vulnerable to heat owing to the diminished thermoregulatory ability with age (e.g., reduced sweat gland output, reduced skin blood flow and smaller

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increase in cardiac output), as well as the increased likelihood of living alone, physical inactivity, having chronic disease and taking medications (Kenney and Munce, 2003; Hajat et al., 2010). Given the global warming scenarios, plus the world's population aging that may amplify heat-related mortality (Li et al., 2016), investigating the health impacts of heatwave on older people is imperative (Guo et al., 2012; Bobb et al., 2014).

In the assessment of heatwave effects, a key issue to be considered is the short-term mortality displacement (or "harvesting"), a phenomenon often noted in many locations suggesting that heat will cause not only the sudden increases in deaths during the first few days but also the subsequent significant decreases in deaths (i.e., lower-than-expected mortality) (Qiao et al., 2015; McGregor et al., 2015; Baccini et al., 2013; Hajat et al., 2005; Guo et al., 2014). It is likely that a proportion of deaths are those that have only been brought forward by a few days as a result of the extreme weather, or occur in already frail individuals and with a very short life expectancy (Baccini et al., 2013; Qiao et al., 2015; McGregor et al., 2015). Mortality displacement thus could have great influence on the actual heat-induced burden of death (McGregor et al., 2015), as shown in a European study reporting the reduction of heat impacts by 75% allowing for mortality displacement (Baccini et al., 2013).

However, existing studies of heatwave and mortality focus largely on acute exposure effects and qualitative analysis (e.g., relative risk and percent change) (Tong et al., 2014, 2015; Ma et al., 2015; Anderson and Bell, 2011). A key question for policy makers and stakeholders arises as to how many or to what extent deaths can be attributable to heatwave exposure, and whether it is urgent or cost-effective to develop and implement targeting policies and intervention measures. The answer relies on a reliable estimate of the burden of heatwave on mortality, including taking into account potential harvesting effect and employing more informative health risk assessment indicators, attributable risk and years of life lost for example (Steenland and Armstrong, 2006; Gasparrini et al., 2015; Huang et al., 2012; Xu et al., 2014). While several recent studies have estimated the premature mortality attributable to ambient temperature (Gasparrini et al., 2015; Yang et al., 2016; Heaviside et al., 2016), few have investigated the mortality displacement and provided estimates of attributable burden for heatwave. Also, health costs due to historical heatwave events remain inexplicit so far.

To address these knowledge gaps, we conducted a time-series analysis involving a large ensemble of the Australian elderly from 1988 through 2011. The objectives of this study were to (i) examine the harvesting effects of heatwave in the elderly across Australian cities; (ii) characterize the mortality risk by heatwave intensity and duration; and (iii) estimate the deaths and health costs attributable to heatwave. All analyses were based on 15-tiered definitions of heatwave with increases in its intensity (a measure for mean temperature on heatwave period) and duration (a measure for heatwave's length in days), and advances in modelling heatwave-mortality relationship to adequately account for mortality displacement.

## 2. Methods

### 2.1. Data collection

#### 2.1.1. Mortality data

This study was conducted in the five largest cities in Australia (Sydney, Melbourne, Brisbane, Perth and Adelaide), which are home to most of Australian population (Supplementary Fig. 1). These cities are the state capitals of five different states with distinct climate and demographic contexts (Supplementary Fig. 2). Daily death counts were acquired from Australian Bureau of Statistics in different periods between 1988 and 2011. The broad health impacts of heat are known to involve almost the whole disease spectrum (Gasparrini et al., 2012; Kim et al., 2015), so we used all-cause mortality data in order to estimate the overall death burden caused by heatwave. We restricted the study population to the elderly (≥75 years), considering that this group of people is generally at highest likelihood of dying from heat and likely contributes the largest part of heat-associated deaths across the whole age range (Baccini et al., 2013; Yang et al., 2015; Tong et al., 2014, 2015; Ma et al., 2015; Ng et al., 2016; Coates et al., 2014; Chen et al., 2015). In addition, mortality displacement phenomenon is more likely to happen in the older elderly and recent researchers believe it is necessary to push back the definition of old age to 75 years of age in view of progressively aging society and raised average life expectancy (Ouchi et al., 2017).

#### 2.1.2. Exposure data

Daily weather data, including maximum temperature and minimum temperature, were downloaded from Australian Bureau of Meteorology's online database. The location of weather station for each city is shown in the Supplementary Fig. 3. We used the daily mean temperature, averaged values of daily maximum temperature and daily minimum temperature, as the exposure index. This choice is in line with recent burden-of-disease research of temperature and mortality (Gasparrini et al., 2015; Huang et al., 2012), and our previous analyses suggesting mean temperature was a slightly better predictor of mortality compared with maximum or minimum temperature in Australia (Yu et al., 2010; Vaneckova et al., 2011). Additional information such as relative humidity and air pollution measures were collected in a subset of cities and used in sensitivity analyses.

We considered 15-tiered definitions of heatwave to capture and characterize the effects of heatwave. In keeping with previous studies (Tong et al., 2015; Cheng et al., 2016; Anderson and Bell, 2011), a heatwave within a region was defined as daily mean temperature above certain percentile of the temperature distribution that lasts for several days in the warm season (November to March of next year). We set the intensity of heatwave at 95th to 99th percentile of temperature distribution, since our previous analyses showed that heatwave effects on the mortality in Australia started to increase around the 95th percentile and rose alarmingly at the 99th percentile (Tong et al., 2015), and set the duration of heatwave at two to four days in case "zero" heatwave event may happen in most cities. Details on definitions of heatwave and its characteristics are provided in the Web Appendix (Supplementary Table 1).

### 2.2. Statistical analyses

#### 2.2.1. First-stage: modelling heatwave-mortality association

We performed a standard time-series quasi-Poisson regression analysis in each city (Gasparrini et al., 2015; Guo et al., 2017), to explore the association between heatwave and mortality. Heatwave as the binary independent variable (1 for heatwave days and 0 for non-heatwave days), and daily count of deaths as the dependent variable were included in the distributed lag non-linear model (Gasparrini, 2014). To control for long term trend and seasonality, we included in the model a natural cubic spline with three degrees of freedom per year for time (Anderson and Bell, 2011; Chen et al., 2015). The day of week was controlled for as a categorical variable. Each year's elderly population in log scale were also included in the model as an offset to control for potential confounding effect of demographic shifts over time (Qiao et al., 2015; Tong et al., 2015).

To detect if mortality displacement does exist across cities, we initially used lags up to 21 days (Qiao et al., 2015). When defining heatwave as ≥2 days with temperature ≥ 96th percentile, except for Brisbane, the remaining four cities saw evident mortality displacement that manifested as negative estimates (relative risk) following the positive estimates in the first few days (Supplementary Fig. 4). Noticeably, subjective selection of the lag may result in inaccurate estimation of heatwave impacts; for example, using a few lag days sometimes cannot capture the mortality harvesting effects, and too many days are likely to generate underestimation of heat-related deaths if mortality harvesting

is transient or even does not exist (Hajat et al., 2005; Qiao et al., 2015; Guo et al., 2017). The optimal lag in the present study was selected based on the generalized cross-validation (GCV) scores derived from regression models. Considering tens of heatwave definitions used, for each city, we finally chose the median value (rounded to integer) of optimal lags (Supplementary Fig. 5), because the distribution of model's GCV scores across all heatwave types was skewed (Supplementary Fig. 6). The selected city-specific lags were different, ranging from one day of lag in Perth to ten in Brisbane (Supplementary Table 2). Similar method has been employed in our previous research in determining the appropriate modelling parameters for assessing heat-related harvesting effects (Qiao et al., 2015). The adequacy of the models was checked by verifying the residuals were approximately normally distributed and independent over time (Huang et al., 2012).

To reflect the death risk of heatwave, we estimated the relative risk and 95% confidence interval (CI) over the lags used for each city (Qiao et al., 2015; Guo et al., 2017). These estimates were then pooled to represent the average level in Australia using empirical Bayes meta-analysis (Viechtbauer, 2010). To explore potential variations in the effects of heatwave between cities, we also used city-specific indicators, including weather (average temperature and temperature range), climate zone (subtropical and temperate) and demography (proportion of population aged ≥75 years), as meta-predictors in the random-effects meta-regression model. These effects were tested through the Wald test, and residual heterogeneity was tested and then quantified by the Cochran Q test and $I^2$ statistic (Gasparrini et al., 2015; Guo et al., 2017).

#### 2.2.2. Second stage: attributable risk calculation

As with previous studies (Gasparrini et al., 2015; Vardoulakis et al., 2014), the burden-of-disease measures, i.e., attributable fraction (AF) and attributable number (AN), were used to calculate the total deaths attributable to heatwave. We did not apply the commonly used method that estimates the excess deaths by subtracting the expected mortality during a pre-defined period from the observed mortality during heatwave period, because this method seems to be useful for the very unusual or unprecedented heatwave events (e.g., 2013 Europe heatwave), and such estimates can be sensitive to the selected baseline mortality (WHO, 2015). Hence, the AF and AN for each heatwave definition (i) in city (j) were estimated from relative risk derived from the first-stage analysis and deaths (D) summed over all identified heatwave episodes (n), using the formulae:

$$AF_{ij} = \frac{RR_{ij} - 1}{RR_{ij}} \tag{1}$$

$$AN_{ij} = AF_{ij} \sum_{1}^{n} D_{ij} \tag{2}$$

We calculated the crude number of deaths attributable to different heatwaves for each city using formula (2). To highlight the between-city difference in the attributable risk, the elderly death rate was also calculated through dividing the calculated crude number by the total number of elderly population in a city.

#### 2.2.3. Third-stage: estimation of heatwave-associated health costs

Although the valuation of a life has long been a controversial issue, the concept of "statistical life" has been developed allowing for the limited public health resources and for the purposes of policy making (Huang et al., 2013; Carmona et al., 2016). To value the statistical life, a number of health outcome measures, such as years of life lost, together with a variety of assessing methods, such as human capital and willingness-to-pay approaches, are already available (Huang et al., 2013). In Australia, a threshold of AUD $40,000 per year of life is often employed by Australian resource allocation committees, for example, the Pharmaceutical Benefits Advisory Committee (Huang et al., 2013; George et al., 2001). It means that interventions saving a year of life in Australia for every AUD $40,000 invested are cost-effective and are very likely to be funded.

Consistent with our previous studies into temperature-associated health costs (Huang et al., 2013; Xu et al., 2014), we in the present study estimated health costs from heatwave exposure in monetary term by combining years of life lost with the economic threshold of AUD $40,000 per year of life. Years of life lost was calculated from Australian national life tables for the years 2002 to 2004 (Huang et al., 2013; Xu et al., 2014). Because the mortality data is collected at the aggregated level that covers relatively narrow age range (≥75), we assumed that all deaths occurred at the age of 75 or at the age in the highest interval in national life tables, so as to gauge the range of total years of life lost attributable to heatwave. In addition, we restricted the calculation to the year 2000 and onward to reduce the influence of changes in average life expectancy and costs of saving a year of life over time.

All the analyses were performed with R software (version 3.4.0). The "dlnm" and "mgcv" packages were used to construct distributed lag non-linear model, "metafor" package for conducting meta-analysis, and "ggplot2" package for map plotting.

## 3. Results

### 3.1. Descriptive analysis

This study included a total of 368,767 elderly deaths, of which, 72,406 (20%) were from the subtropical regions. Table 1 summarises the main data characteristics for selected cities in Australia, with the study period, elderly population, elderly deaths and mean temperature. As expected, subtropical region, compared with temperate region, had higher values in daily mean temperature, ranging from 24.1 °C in Brisbane to 20.0 °C in Melbourne. The number of daily deaths ranged from 11.2 (standard deviation: 3.9) in Perth to 36.9 (standard deviation: 7.9) in Sydney.

Supplementary Table 1 shows the heatwave characteristics and daily mean temperature on heatwave days for each city. During the study period, the total number of heatwave days that occurred ranged from several to > 100, depending on heatwave intensity and duration, and varying between and within cities. Similar patterns were also observed for the daily mean temperature during heatwave period, but noticeably, the highest mean temperature, regardless of the heatwave

**Table 1**
Characteristics of study period, elderly population, elderly deaths and temperature in warm season (November, December, January, February, March) in the five largest cities of Australia.

| City | Study period | Elderly population (annual) | Fraction of elderly (%) | Total elderly deaths | Daily elderly deaths (mean and SD) | Daily mean temperature (mean and range, °C) |
|---|---|---|---|---|---|---|
| Adelaide | 1988–2009 | 72,357 | 6.59 | 43,042 | 12.9 (4.1) | 21.8 (11.8–38.7) |
| Brisbane | 1997–2011 | 91,259 | 5.07 | 35,085 | 15.7 (5.1) | 24.1 (16.8–34.2) |
| Melbourne | 1988–2011 | 186,872 | 5.37 | 119,706 | 33.0 (7.6) | 20.0 (10.0–35.4) |
| Perth | 1988–2009 | 65,739 | 4.86 | 37,321 | 11.2 (3.9) | 22.9 (11.1–35.6) |
| Sydney | 1988–2011 | 214,703 | 5.31 | 133,613 | 36.9 (7.9) | 22.0 (12.5–33.8) |

SD is the standard deviation.

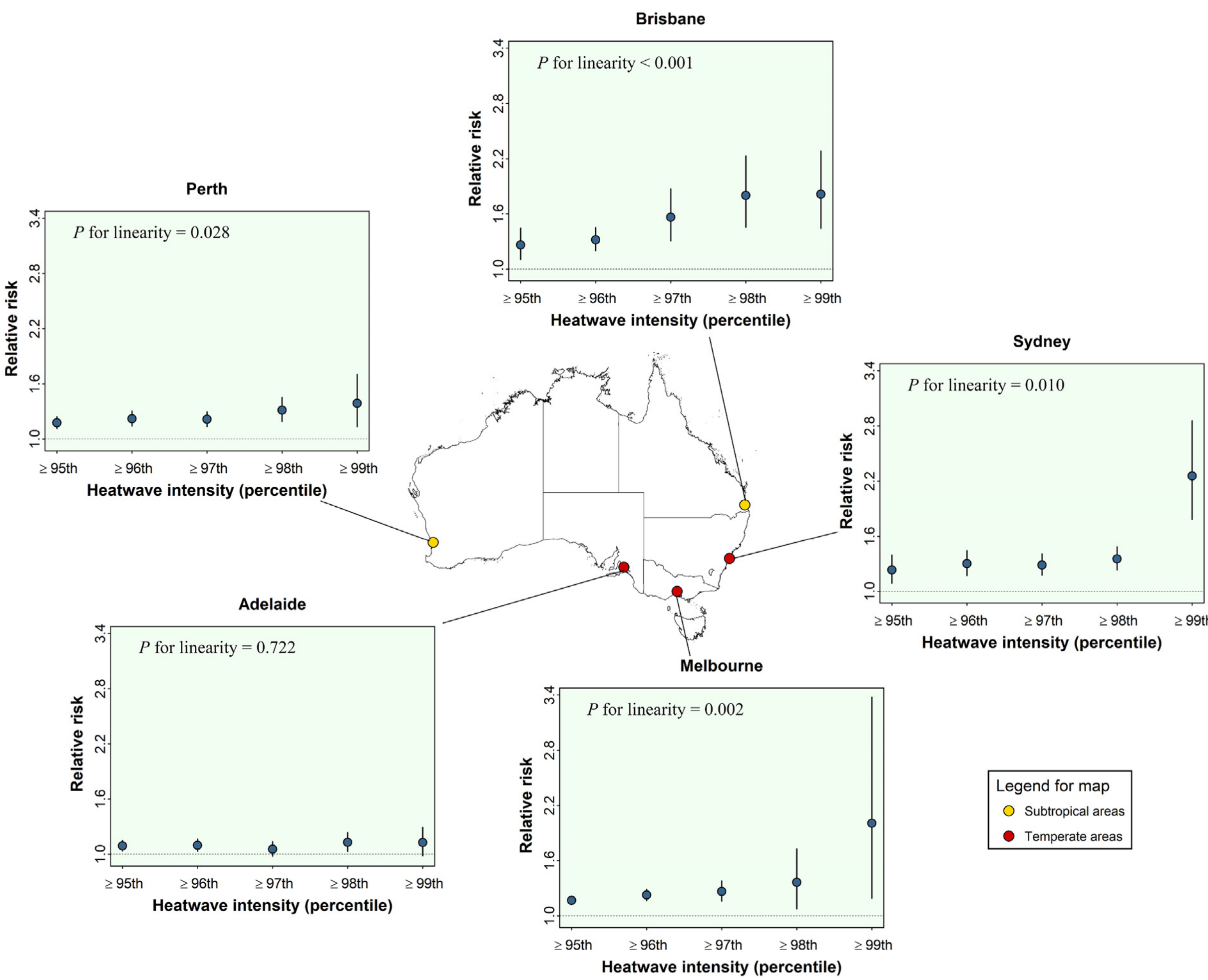


**Fig. 1.** Estimated relative risk of death for heatwave with different intensities in five Australian cities.
Points indicate the estimated relative risk, and lines are the 95% confidence interval; Linear trend of estimated relative risks over heatwave intensity was tested using meta-regression with intensity (percentile) as the continuous variable.

intensity and duration, has exceeded 30 °C in most cities, and sometimes reached over 35 °C in some cities.

### 3.2. Relative risk of death

Fig. 1 shows the heatwave-related relative risk for death in each city, under different heatwave intensity, from ≥95th percentile (the least severe) to ≥99th percentile (the most severe). A consistent and statistically significant increase in risk during heatwave days versus non-heatwave days was observed in all cities. We also found higher risk for death with more intense heatwave in four out of five cities, although the increasing pattern and exact relative risk estimates seemed to be different from one city to another. However, obvious evidence of higher relative risk with longer-lasting heatwave was found only in one city (Perth) (Fig. 2).

Table 2 reports the overall heatwave effects for each city, different climate zones, and the whole of Australia. It was estimated that the risk of death, on average, increased by 28% (95% CI: 15% to 42%) in Australia, with the increase in death ranging between 9% and 49% across cities, and between 24% and 34% across different climate areas. There is also evidence that heatwave effects differed among cities (*P*-value $< 0.001$), as well as between temperate and subtropical regions (*P*-value $< 0.05$).

Further multivariate meta-regression analyses into heterogeneous heatwave effects indicate that, the residual heterogeneity still remained relatively high, even after city-specific indicators (average temperature, temperature range, climate zone and elderly fraction) were included as the meta-predictors, with an $I^2$ of 79.74% (Supplementary Table 3). Although several predictors can significantly modify the heatwave effects in either single-predictor or full-predictor models, only small amount of heterogeneity can be explained by the included city-specific indicators, as indicated by the small drops in the $I^2$ statistics.

### 3.3. Attributable risk of heatwave

The heatwave-related death burden, estimated as the daily attributable number of deaths, is shown in Table 3 and Supplementary Fig. 7. Daily number of deaths due to heatwave appeared to increase with more intensive heatwave (from 95th percentile to 99th percentile) in most cities, whereas the actual number were different, broadly ranging from 2 to 15 deaths per 100,000 elderly population per day (Supplementary Fig. 7). Also, the characteristics of death burden associated with heatwave duration were not identical across cities (Table 3). For example, across all types of heatwave intensity, daily attributable number of deaths, in terms of crude number or standardized number (per 100,000 elderly population), consistently increased with heatwave duration in Brisbane, while the biggest estimates in Melbourne were generally found for heatwave with a duration of ≥3 days.

In other cities, daily attributable number of deaths under certain heatwave intensities likely presented upward or downward trend with increases in heatwave duration, or the largest for heatwave with a

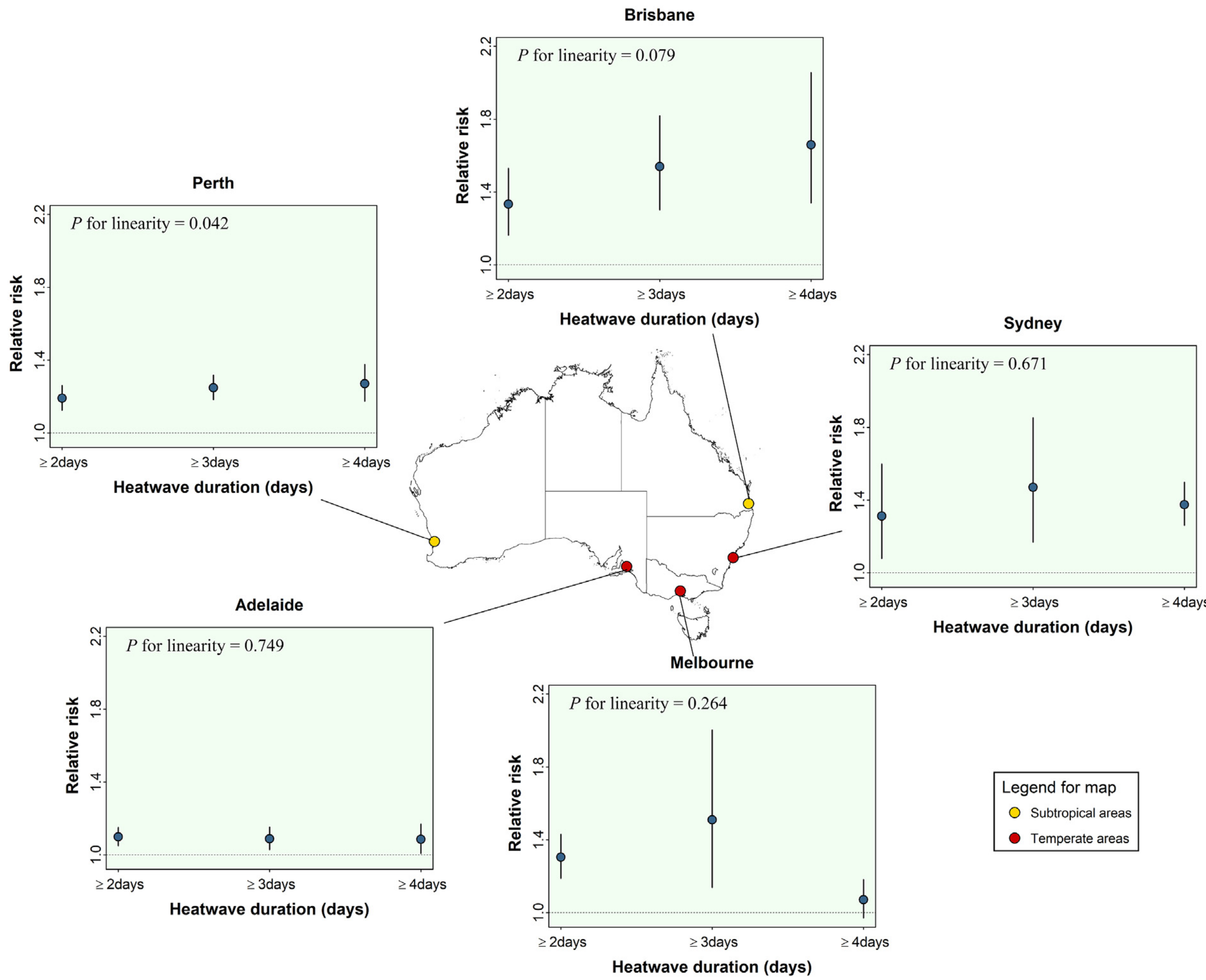


**Fig. 2.** Estimated relative risk of death for heatwave with different durations in five Australian cities.
Points indicate the estimated relative risk and lines are the 95% confidence interval; Linear trend of estimated relative risks over heatwave duration was tested using meta-regression with duration (days) as the continuous variable.

**Table 2**
Overall heatwave effects on mortality by city and climate zone.

| Region | Heatwave effects (95% CI) | *P*-value |
|---|---|---|
| City | | |
| Adelaide | 1.09 (1.06 to 1.13) | |
| Brisbane | 1.49 (1.35 to 1.65) | |
| Melbourne | 1.31 (1.16 to 1.47) | < 0.001 |
| Perth | 1.21 (1.18 to 1.25) | |
| Sydney | 1.36 (1.23 to 1.50) | |
| Climate zone | | |
| Subtropical | 1.33 (1.09 to 1.64) | 0.046 |
| Temperate | 1.24 (1.08 to 1.42) | |
| National | 1.28 (1.15 to 1.42) | |

The heatwave effects were derived by pooling the estimates of all heatwave definitions for each city and different climate zones.
Effect difference between cities was tested with analysis of variance, and between climate zones with meta-analysis.

duration of ≥ 3 days. Overall, at the national level, when the heatwave intensity fell between 96th and 99th percentiles, the heatwave with a duration of ≥ 3 days resulted in the most deaths, while increased deaths with longer-lasting heatwave could be seen only when the heatwave intensity came up to 95th percentile (Table 3).

### 3.4. Monetary estimates of annual health costs due to heatwave

For all the cities studied, the health costs resulting from past heatwaves, albeit occurred at different intensities, could reach several million Australian dollars each year (Table 4). Specifically, annual health costs due to heatwave were estimated to be less than AUD $5 million in some cities, such as Adelaide and Perth, while other cities, such as Sydney, Melbourne and Brisbane, have seemingly suffered greater health costs, in excess of AUD $10 million or even AUD $20 million.

### 3.5. Sensitivity analyses

To test the robustness of our results, we did several sensitivity analyses by (i) changing the degrees of freedom for secular and seasonal control; (ii) alternatively using the optimal lags (city-specific mean values and rounded to integer across all heatwave types); and (iii) additionally adjusting for relative humidity and air pollutants (Supplementary Table 4). All sensitivity analyses suggested analogous results and confirmed our approaches are independent on modelling assumptions.

**Table 3**
Comparisons of the daily attributable deaths during heatwaves with different durations for each city and the Australia, presented as the elderly death rate (per 100,000 elderly population), and crude number in parentheses.

| Heatwave definitions | Adelaide | Brisbane | Melbourne | Perth | Sydney | National |
|---|---|---|---|---|---|---|
| ≥95th percentile | ▲ | ▼ | ▲ | ▲ | ▼ | ▼ |
| & ≥2 days | 1.73 (1.25) | 2.02 (1.84) | 2.84 (5.31) | 2.05 (1.35) | 2.10 (4.50) | 2.15 |
| & ≥3 days | 1.80 (1.30) | 4.42 (4.03) | 2.99 (5.58) | 3.53 (2.32) | 3.61 (7.76) | 3.27 |
| & ≥4 days | 1.16 (0.84) | 6.29 (5.74) | 1.43 (2.68) | 3.22 (2.12) | 6.47 (13.89) | 3.71 |
| ≥96th percentile | ▲ | ▼ | ▲ | ▼ | ▼ | ▲ |
| & ≥2 days | 1.73 (1.25) | 3.42 (3.12) | 3.59 (6.70) | 2.45 (1.61) | 3.10 (6.65) | 2.86 |
| & ≥3 days | 1.80 (1.30) | 5.08 (4.64) | 3.84 (7.18) | 3.86 (2.54) | 5.91 (12.68) | 4.10 |
| & ≥4 days | 1.71 (1.24) | 6.17 (5.63) | 1.03 (1.93) | 4.38 (2.88) | 6.47 (13.89) | 3.95 |
| ≥97th percentile | θ | ▼ | ▲ | ▼ | ▲ | ▲ |
| & ≥2 days | 1.34 (0.97) | 5.17 (4.72) | 4.29 (8.02) | 2.86 (1.88) | 3.54 (7.61) | 3.44 |
| & ≥3 days | 0.79 (0.57) | 7.74 (7.06) | 5.09 (9.52) | 3.50 (2.30) | 6.63 (14.23) | 4.75 |
| & ≥4 days | 0.59 (0.43) | 9.76 (8.91) | 1.03 (1.93) | 4.43 (2.91) | 5.87 (12.61) | 4.34 |
| ≥98th percentile | ◆ | ▼ | ▲ | ▲ | ▲ | ▲ |
| & ≥2 days | 2.40 (1.74) | 7.44 (6.79) | 5.89 (11.01) | 4.32 (2.84) | 5.52 (11.85) | 5.11 |
| & ≥3 days | 1.93 (1.40) | 10.39 (9.48) | 9.83 (18.37) | 4.56 (3.00) | 6.63 (14.23) | 6.67 |
| & ≥4 days | 4.09 (2.96) | 11.52 (10.51) | 1.03 (1.93) | 4.43 (2.91) | 5.87 (12.61) | 5.39 |
| ≥99th percentile | ◆ | | | | | ▲ |
| & ≥2 days | 2.61 (1.89) | 8.53 (7.78) | 8.14 (15.21) | 6.15 (4.04) | 11.98 (25.72) | 7.48 |
| & ≥3 days | 1.99 (1.44) | 11.69 (10.67) | 21.93 (40.99) | NA | 13.11 (28.15) | 12.18 |
| & ≥4 days | 3.68 (2.66) | NA | NA | NA | NA | 3.68 |

The crude number of deaths was calculated using formula (2).
The elderly death rate (per 100,000 elderly population) was computed via simply dividing the number of attributable deaths (crude number) by the total number of the elderly (≥75) without considering age-specific interval.
Heatwave was defined as ≥2 to 4 days with temperature ≥ 95th to 99th percentile.
NA indicates no heatwave events identified.
▼ indicates an uptrend with the increase of heatwave duration; θ indicates a downtrend with the increase of heatwave duration; ▲ refers to the maximum value for the heatwave with a duration ≥3 days; ◆ refers to the minimum value for the heatwave with a duration ≥3 days.

**Table 4**
Monetary estimates of annual health costs due to heatwave with different intensities in five cities in Australia, 2000–2011 (AUD $ million).

| Heatwave | Adelaide | Brisbane | Melbourne | Perth | Sydney |
|---|---|---|---|---|---|
| ≥95th percentile | 0.97 to 4.47 | 1.28 to 5.90 | 3.30 to 15.23 | 0.73 to 3.37 | 2.68 to 12.39 |
| ≥96th percentile | 0.79 to 3.66 | 1.88 to 8.66 | 3.49 to 16.10 | 0.78 to 3.58 | 2.97 to 13.70 |
| ≥97th percentile | 0.57 to 2.63 | 2.61 to 12.05 | 3.36 to 15.50 | 0.80 to 3.70 | 2.85 to 13.14 |
| ≥98th percentile | 0.87 to 4.03 | 3.21 to 14.82 | 3.67 to 16.92 | 0.74 to 3.41 | 4.78 to 22.08 |
| ≥99th percentile | 0.69 to 3.18 | 3.64 to 16.81 | 4.31 to 19.90 | 0.89 to 4.11 | 5.93 to 27.38 |

Estimates were derived based on the years when heatwave events occurred, since heatwave did not take place every year during the study period.
Average currency exchange rate in August 2017: 1 AUD ≈ 0.78 USD.

## 4. Discussion

### 4.1. Principal findings

This large retrospective observational study in Australia suggested that exposure to heatwave was significantly associated with the mortality among the elderly aged ≥75 years. Importantly, this association is characterized by the pattern that adverse effects (relative risk > 1.0) appeared immediately and persisted in the first few days, followed by the protective effects (relative risk < 1.0) that is consistent with the short-term mortality displacement. After optimizing lags for fitting heatwave-mortality association, estimated relative risks for death across cities were between 1.09 and 1.36, with a national average of 1.28 (95% CI: 1.15 to 1.42). These risks, on the whole, seemed to be larger when the heatwave was more extreme in its intensity, and in subtropical area versus temperate area. In every city heatwave was responsible for many deaths every day, ranging from several to dozens of deaths, with noted variations by heatwave intensity and duration. Also, these heatwave-associated deaths equate to an enormous economic loss for every city, reaching several million Australian dollars each year depending on the location and heatwave characteristics.

### 4.2. Comparison with other studies

One notable finding is the short-term mortality displacement after heatwave. The possible reason is that some elderly people or chronically ill individuals who would die anyway within a short period and their imminent death is simply hastened by the heatwave (Hajat et al., 2006; Qiao et al., 2015), a sudden environmental stress that can trigger a series of changes in individuals (e.g., increased heart and respiratory rates, dehydration, and damage to the brain, kidneys and liver) and exacerbate pre-existing diseases (Seltenrich, 2015). Evidence of mortality displacement has also been observed in a handful of previous studies of heatwave involving the whole age group (Kyselý, 2004; Hajat et al., 2006; Le Tertre et al., 2006; Kaiser et al., 2007; Guo et al., 2017). Nevertheless, the dominating research focus in published literature is now on the immediate and adverse effects of heatwave that occur on the current day or within a few days (Tong et al., 2014, 2015; Ma et al., 2015; Anderson and Bell, 2011; Xu et al., 2016; Madrigano et al., 2015), indicating the existing body of knowledge on how heatwave affects mortality should be further updated. In addition to the widely observed abnormal increases in deaths during heatwave period, obvious drops in mortality after heatwave could also be seen. Most likely, the overall impact of heatwave could have been overestimated in many previous studies that only assessed acute heatwave exposure if the heatwave-harvesting effect does exist in the studied areas (Kyselý, 2004; Le Tertre et al., 2006; Kaiser et al., 2007).

We also surprisingly found that, across cities, heatwave impact on mortality significantly differed in the length of lags (Supplementary Table 2), which is contrast to most multi-region/country studies acquiescently assuming the uniform lag for fitting heatwave-mortality association and then comparing the effect estimates over the same lag scale (Tong et al., 2014, 2015; Ma et al., 2015; Sheridan and Dixon, 2016; Guo et al., 2017). A recent international study showed evidence

that components of short-term heatwave impacts consist of initial increases in risk in all affected regions/countries, and later decreases in risk in several regions/countries, such as USA, UK and Australia (Guo et al., 2017). This difference could reflect geographical variations in population's physiological and behavioral acclimatization, adaptation responses and susceptibility factors, and consequently result in diverse human responses to heatwave (Hajat et al., 2010; McMichael et al., 2006). One of the important contributors to the difference may be due to the local heat intervention policies. For example, whether or not early heat alert and prevention measures (e.g., medical services preparation and heat-protection advices) would be released to the public, to some extent, affects if and how people will protect themselves and, in the end, determine the size and length of heat impacts (Hajat et al., 2010). The timing, frequency and duration of the launched protective programs, and the awareness of the hazardous heat are also likely to affect the population vulnerability within a given region, as shown in Fig. 2 (the pattern of heatwave effect was not consistent across studied regions, with the largest effect observed for heatwave lasting for > 2 and 3 days). The widespread inconsistent temperature-mortality association, such as region-specific comfort temperatures corresponding to the minimal mortality and slopes of exposure-response curves, represent another geographical difference (Gasparrini et al., 2015; Díaz et al., 2015). With respect to the underlying drivers for the observed between-region differences in the effects of heatwave, several factors at the city level included in the present study failed to adequately address residual heterogeneity (Supplementary Table 3), which validated our previous findings at the country level (Guo et al., 2017). Other factors including population density, air conditioning usage, green space coverage and socio-economic status also play the key role in determining the population's vulnerability to heatwave within a region (Medina-Ramón and Schwartz, 2007; Son et al., 2016; Benmarhnia et al., 2017; Madrigano et al., 2015; Ma et al., 2015).

The magnitude of the health effects of a heatwave also depends on its own characteristics, and significant effect modification by heatwave intensity and duration were often reported previously (Guo et al., 2017; Anderson and Bell, 2011; Chen et al., 2015; Tong et al., 2015; Barnett et al., 2012). These studies have consistently demonstrated that more intensive heatwave was associated with higher risk of death, but to date it remains unclear as to whether this pattern will change in regions having mortality displacement that can offset in part the harmful effects of heatwave. For this case, the present study supported and further consolidated previous finding about the influence of heatwave intensity (Fig. 1). By contrast, findings of how the effects of heatwave change with its own duration have been mixed. Some studies reported evidence of upward tendency with heatwave duration (Anderson and Bell, 2011; Barnett et al., 2012), while other studies did not find out any apparent tendency (Guo et al., 2017; Chen et al., 2015), as similarly found in this study (Fig. 2). A possible explanation is that the effects of sustained duration of heat, also known as the added heatwave effect (Gasparrini and Armstrong, 2011), does not exist in all affected regions, but in limited regions (Guo et al., 2017; Gasparrini and Armstrong, 2011; Huang et al., 2012). Therefore, in general heatwave intensity likely plays a relatively more important role than duration in determining the population's vulnerability to heatwave (Xu et al., 2016), even at the national and global scale (Tong et al., 2015; Guo et al., 2017).

As a supplement to relative risk assessment, this study additionally estimated the deaths attributable to heatwave. This analysis extends previous research that predominantly examined the relative risk of mortality, which is heavily influenced by deaths in frail elderly people, mortality displacement and exposure characteristics (e.g., low relative risk of death could result in tremendous burden due to frequent exposure within a very large pool of vulnerable populations) (Huang et al., 2012; Hajat et al., 2006; Steenland and Armstrong, 2006; Gasparrini et al., 2015). An increasing number of studies report the attributable risk for ambient temperature (Gasparrini et al., 2015; Yang et al., 2016; Kim et al., 2015), most of which investigated daily ambient temperature rather than heatwave, and very few have done the analysis of attributable risk for heatwave. A nation-wide study in Spain reported several deaths per day attributable to extreme high temperature, the "trigger point" for heatwave (Carmona et al., 2016; Díaz et al., 2015). Further scale-up to extreme or unprecedented heatwave event, like 2003 European heatwave and 1995 U.S. heatwave (Le Tertre et al., 2006; Kaiser et al., 2007), it accounted for dozens of deaths per 100,000 population per day, which is consistent with our findings. Apart from such analyses of single or several heatwave events, this study systematically compared the deaths attributable to different types of heatwave, suggesting the pattern of increased deaths associated with more intense heatwave and the largest number of deaths mostly occurred on ≥3 days heatwave for the whole Australia (Table 3, Supplementary Fig. 7). However, no such investigations appear yet to have been undertaken, so it is hard to say whether in other countries there would have been similar pattern of attributable risk with heatwave characteristics.

### 4.3. Implications for future heatwave research and public health policy

The findings of this study strongly support the need in future heatwave research to consider the possible mortality displacement. Although recent studies have revealed evident heat-harvesting effects in many regions of the world (Guo et al., 2014; Qiao et al., 2015), it is noteworthy that this pattern may be different for heatwave and regular heat, because the former could produce the dual stress from both single day's high temperature (i.e., regular heat) and several consecutive day's high temperature (i.e., added heatwave effect) (Gasparrini and Armstrong, 2011; Hajat et al., 2006). However, some previous studies of heatwave tended to focus on added heatwave effects by adjusting for temperature (as a continuous variable), which is different from other studies and the present study that estimated heatwave effects using dummy variables for heatwave ('yes' for heatwave days and 'no' for non-heatwave days) without including the temperature as the continuous variable in the model (Gasparrini and Armstrong, 2011; Guo et al., 2017). The importance of added heatwave effects in the overall heatwave effects remains an unresolved issue and needs to be clarified in the future study. Given the geographically heterogeneous human responses to heatwave, it is essential to use region-specific lags for fitting heatwave-health association, and to unravel the possible reasons for spatial variations in the effects of heatwave (Guo et al., 2017).

It is now achievable to accurately forecast heatwave weather, and some of deaths due to heatwave can be avoided via joint efforts of government, individuals and care-givers of at-risk people. This study demonstrates that should heatwave warning systems be successful a large number of deaths can be saved, which is equivalent to making big profits in economy in Australia and elsewhere (Huang et al., 2013; Carmona et al., 2016). Additionally, developing heatwave response plans at both national and regional level are necessary (Xu et al., 2016), because on the one hand health impacts increase with more intensive heatwave without geographical restriction, but on the other hand there has been regional heterogeneity in the pattern of health impacts with heatwave duration (Guo et al., 2017).

### 4.4. Strengths and limitations of the study

This study had some limitations. Firstly, we used the elderly population in Australia as a case study, which likely limits the extrapolation of our findings to other countries/regions. Secondly, daily temperature data was collected from fixed monitoring stations, rather than at individual exposure level, which may result in an underestimation of the estimated effects of heatwave (Lee et al., 2016). Thirdly, we did not control for air pollutants and relative humidity in the main model as these data were not available for all cities, but we believe that our results would be little affected because our sensitivity analyses and previous studies suggest the robust heatwave-mortality

association, independent of these confounding factors (Anderson and Bell, 2009; Tong et al., 2010, 2014). As for other countries/regions that are seriously impacted by air pollution, such as China (Guan et al., 2016; Guo et al., 2013), air pollution may, to some extent, mediate the effects of heatwave on mortality (Chen et al., 2017). Fourth, for each heatwave type we assumed that the heatwave effects remain unchanged over time. However, previous research indicated that the effect size of heatwave changes from year to year (Guo et al., 2012), and from day to day (Le Tertre et al., 2006), and thus our assumption may influence the accuracy of estimating the attributable deaths for heatwave. Fifth, although we used an innovative way to model the heatwave-mortality association, the used lag days were relatively short, and the characteristics of the mortality displacement may not be wholly captured in assessing overall heatwave effects. It is challenging to simultaneously consider the geographical variation in the length of lag effects and mortality displacement of heatwave, which warrants future exploration. Sixth, the elderly population is considered as an economic burden because they are more likely to develop chronic diseases and create lower or no social value after retirement compared with other age groups. In this case, using the threshold of AUD $40,000 per year of life that do not consider the differences in life expectancy and value of statistical life between different age groups may influence the accurate estimation of the economic burden from heatwave-related elderly mortality.

Despite these limitations, to our knowledge this study to date is the largest and the most comprehensive research into the burden of heatwave on the elderly mortality in Australia. On the basis of our previously established tiered heatwave definitions (Tong et al., 2015), we systematically examined the heatwave-mortality association, including the acute adverse effects of and potential harvesting effects of heatwave. Relative mortality risks associated with different heatwave characteristics were also analyzed. Furthermore, we quantitatively estimated the deaths attributable to heatwave, explored how this estimate varied with heatwave characteristics, and finally used an innovative health indicator - years of life lost as a bridge to estimate and report the potential economic loss attributable to the past heatwaves (Huang et al., 2013; Xu et al., 2014).

## 5. Conclusions

Overall, this study highlights the opposite impact of heatwave in the short term, with rapid increase in mortality within the first few days being followed by unexpected decreases in mortality among the elderly in Australia. Substantial deaths and enormous economic loss attributable to heatwave at city level have also been expected. As global warming and population aging proceed throughout the 21st century, using the traditional health risk assessment measures, such as relative risk and odds ratio, in conjunction with more informative health measures, such as attributable risk and year of life lost, will assist in improving our understanding of the complex relation between heatwave and changes in health risk, as well as providing health policy-oriented evidence basis for the development of heatwave warning system and intervention strategies.

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## Conflict of interest

The authors declare no conflict of interest.

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## Appendix A. Supplementary data

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