Temporal trends of the association between ambient temperature and cardiovascular mortality: a 17-year case-crossover study

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Abstract

Aim. To examine the temporal variations of the association between ambient temperature and mortality for cardiovascular diseases in Queensland, Australia between 1997 and 2013.

Methods. We obtained 147,238 cardiovascular deaths data from Queensland Health between 1 January 1997 and 31 December 2013. Time-stratified case-crossover design was fitted via the conditional quasi-Poisson regression with time-varying distributed lag non-linear model to estimate the associations between temperature and cardiovascular mortality. Stratified analyses were performed by age, sex, climate zone, and socioeconomic status.

Results. We found a substantial decrease in the cold effect, while there was no significant change in the heat effect. Results of subgroup analyses showed an increasing trend for heat effects in men, people \(\leq 84\) years old, those living in low and middle socioeconomic areas and those living in hot climate areas. There was a decreasing trend for the magnitude of associations between temperature (both cold and hot temperatures) and cardiovascular mortality in people \(\geq 85\) years old and in areas of high socioeconomic status.

Conclusions. The associations between cold temperature and cardiovascular mortality decreased in Queensland, Australia between 1997 and 2013, but no declines were observed for hot temperatures. Men, people \(\leq 84\) years old, people living in low and middle socioeconomic score areas and people living in hot climate areas demonstrated increased susceptibility to hot temperatures. Our findings suggest a need for heat awareness health promotion campaigns to enhance adaptation to a warming climate among vulnerable population.

1. Introduction

Cardiovascular diseases are one of the largest public health problems worldwide and are the leading cause of death globally, accounting for 319.6 million years of life lost in 2016 [1, 2]. Deaths from cardiovascular diseases have increased by 41\% between 1990 and 2013, which continue to rise as a result of the aging of the population and other epidemiological risk factors [3]. In 2017, 27\% of all deaths in Australia can be attributable to cardiovascular system diseases [4].

Extreme temperatures have been demonstrated to increase the risks of cardiovascular mortality across a range of geographical regions in the world, with the relationship exhibiting U, V, and J shapes [5–9]. Both extreme cold and extreme hot temperatures are associated with the increase in cardiovascular mortality [10–13]. There is an increasing number of studies examining the temporal trends of temperature-mortality associations, indicating decreasing associations with either hot or cold temperatures or both [14–18]. Most of these studies use all-cause total
mortality as the primary outcome and very few studies involve cardiovascular deaths [19, 20].

One study in London indicated that the cardiovascular mortality associated with cold temperatures declines progressively over the 20th century [19]. Other studies have demonstrated that the heat-related cardiovascular mortality decline more substantially than that of cold-related cardiovascular mortality, especially among the elderly [20–22]. However, the temporal trends in the association between temperature and cardiovascular mortality were inconsistent across different locations. In addition, studies have been conducted to investigate the temporal trends across different age and sex groups. For example, a study in Spain found that the risk of cardiovascular deaths associated with warm and cold temperatures decreased across all age groups between 1980 and 2016 [23]. However, there is no study to further explore whether the temporal trend of temperature-mortality association could be modified by extrinsic factors, such as local climate and socioeconomic status.

In this study, we aimed to use a 17-year data set to examine the temporal variations in the association between ambient temperature and mortality for cardiovascular diseases in Queensland, Australia between 1997 and 2013. We also examined the change in vulnerability among different subgroups, including intrinsic factors groups (age, sex) or extrinsic factors groups (local climate, socioeconomic development).

2. Methods

2.1. Data collection

Daily mortality data between 1 January 1997 and 31 December 2013 in Queensland were collected at the postcode level from Queensland Health. Each death record included date of death, sex, age, and primary causes of death. According to Australian Bureau of Statistics, Queensland has 443 postal areas (Australian Bureau of Statistics, postal areas ASGS Edition 2016). The diagnosis of cardiovascular diseases followed the International Classification of Diseases, 9th Revision (ICD-9: 390–459) during 1997/Jan/01–1999/Jul/31 or 10th Revision (ICD-10: I00-I99) during 1999/Jul/01-2013/Dec/31. We stratified mortality data according to age (0–59, 60–84, ≥ 85 years) and sex (male and female).

We extracted data on daily temperatures (maximum and minimum) at the postal area level from gridded (about 5 km × 5 km resolution) dataset of scientific information for land owners (SILO) hosted by the Science and Technology Division of the Queensland Government’s Department of Environment and Science. Daily mean temperature, i.e. the mean of maximum and minimum temperatures, was applied as the thermal index in this study to analyse the temperature-mortality associations. Daily relative humidity (maximum and minimum) data during the study period were collected from the gridded data set of SILO as well. Daily mean relative humidity was calculated by averaging the data on maximum and minimum relative humidity. The postal areas of Queensland are divided into hot, mild and cold regions according to the characteristics of local daily mean temperature (figure S1 (stacks.iop.org/ERL/16/045004/mmedia)). We extracted the ‘Index of Relative Socio-Economic Advantage/Disadvantage (IRSAD)’ from Socio-Economic Indexes for Areas, Census of Population and Housing (Australian Bureau of Statistics, Australia, 2016). IRSAD represents the relative economic and social conditions of people and households within an area. The postal areas of Queensland are then classified into three parts, i.e. IRSAD high (high socioeconomic status, 143 postal areas), IRSAD middle (middle socioeconomic status, 142 postal areas) and IRSAD low (low socioeconomic status, 142 postal areas) (figure S2)

2.2. Statistical analysis

2.3. Temperature-mortality association

We used time-stratified case-crossover design fitted via the conditional quasi-Poisson regression model to analyse temperature-mortality associations. The principle of this design is that each person is treated as a stratum, where the exposure during the risk period is compared with exposures during the control periods. As with other studies [24, 25] control periods were defined as the same days of the week in the same calendar month of the death. This within-subject comparison theoretically controls for time-constant variables at the individual level, e.g. BMI. This design was adjusted for long-term trend and seasonality [26]. As with previous studies [27], we used the distributed lag nonlinear model (DLNM) to fit the relationship between temperature and cardiovascular mortality, with natural cubic splines with three degrees of freedom (df) for the dimensions of temperature and lag days, respectively. We used lag 0–21 d to fully capture the delayed effects of temperature [28]. The potential confounding effect of relative humidity was controlled for using a natural cubic spline with 3 df for the moving average of 3 d data [27]. We also controlled for public holidays as a binary variable.

2.4. Temporal trends in the temperature-mortality association

We examined the temporal variation of the association between ambient temperature and mortality for cardiovascular diseases using the time-varying DLNM [24]. Briefly, we extended the DLNM by including a linear interaction between the time variable and the cross-basis matrix of the temperature-lag-mortality relationship. We examined whether
Table 1. Distribution of number of deaths and temperature features in the 443 postal areas between 1997 and 2013 in Queensland.

| Subgroup      | No. of cases | Postal area temperatures (°C) |
|---------------|--------------|------------------------------|
|               |              | Mean | Minimum | Maximum |
| Total         | 147 238      | 21.0 | -8.9    | 48.3    |
| 1997          | 8879         | 20.7 | -5.9    | 44.8    |
| 2013          | 8085         | 21.3 | -5.2    | 48.3    |
| **Climate**   |              |      |         |         |
| Hot           | 41 120       | 23.1 | -4.0    | 48.3    |
| Mild          | 70 158       | 20.6 | -4.5    | 46.9    |
| Cold          | 35 960       | 19.2 | -8.9    | 44.5    |
| **IRSAD**     |              |      |         |         |
| Low           | 41 025       | 21.1 | -8.9    | 47.1    |
| Middle        | 45 710       | 21.2 | -8.7    | 48.3    |
| High          | 60 490       | 20.7 | -5.5    | 46.0    |
| **Sex**       |              |      |         |         |
| Men           | 71 345       | -    | -       | -       |
| Women         | 75 886       | -    | -       | -       |
| **Age (years)**|            |      |         |         |
| 0–59          | 11 465       | -    | -       | -       |
| 60–84         | 72 316       | -    | -       | -       |
| 85+           | 63 452       | -    | -       | -       |

there was a temporal difference in the effect of temperature by comparing the relative risks (RRs) in the middle dates of 1997 and 2013.

The results were reported as the RRs with 95% confidence intervals (CIs) of mortality associated with specific temperature values, compared with the minimum mortality temperature (MMT). We defined the cold effect as the RRs at the 1st percentile of temperature versus MMT of the year studied, and the heat effect as the RRs at the 99th percentile of temperature versus MMT of the year studied.

Sub-group analyses were performed to examine the change in vulnerability among different subgroups, including sex, age group (0–59, 60–84, ≥85 years), local climate (hot, mild and cold), socioeconomic development (low, middle, high).

2.5. Sensitivity analyses

To check the robustness of our findings, we changed the df of natural cubic splines from 2 to 4 for temperature and relative humidity. We also changed the maximum lag from 21 d to 28 d for temperatures. Some studies indicated that the effect of heat exposure might last for shorter time than cold effect. To test the reliability of our results on heat effect, we also applied for a shorter-lag i.e. 7 d and 14 d for temperature. We analysed the association between temperature and mortality for cardiovascular diseases in every five years with three years overlapping to check if our time-varying DLNM was robust or not. We did a sensitivity analysis for the 35–59 years age group to check if there was substantial effect difference between 35–59 years age group and 0–59 years age group.

R software (version 3.5.1) was used for all data analyses. The ‘gnm’ [29] and ‘dlm’ [30] packages were used to fit the conditional quasi-Poisson regression model and distributed lag model, respectively.

3. Results

The daily mean temperature increased from 20.7 °C in 1997 to 21.3 °C in 2013 (table 1). During the study period, there were 147 238 deaths (48.5% women) due to cardiovascular diseases (figure 1). Most of the deaths happened in the elderly. The 60–84 years age group took 49.1%. The ≥85 years age group took 43.1%.

The average relationship between temperature and cardiovascular mortality was U-shaped in Queensland during 1997–2013, with the MMT appearing at the 64th percentile, i.e. 23.4 °C (figure 2(a)). Both extreme cold and hot temperatures were significantly associated with increased risks of cardiovascular mortality, with the RRs being 1.48 (95%CI: 1.42, 1.53) and 1.14 (95%CI: 1.10, 1.19), respectively. The cold effect declined significantly (p-value < 0.001) from 1.66 (95%CI: 1.55, 1.78) in 1997 to 1.32 (95%CI: 1.24, 1.42) in 2013 (figure 2(b)). In comparison, there was no significant change for heat effect [1.14 (95%CI: 1.06, 1.23) in 1997 and 1.16 (95%CI: 1.07, 1.26) in 2013; p-value = 0.72].

Figure 3 shows the effect estimates of cold and heat across population subgroups in 1997 and 2013 (see specific RR values in table S2 and the exposure-response relationships in figure S3). The cold effect decreased across all subgroups except for male and the 60–84 years age group. For heat effect, the greatest increase was found in the 0–59 years age group. The similar increasing trend was also found in men, the elderly aged 60–84 years, those living in hot areas, and those in low and middle socioeconomic areas.

Table 2 shows the MMT for cardiovascular diseases of different subgroups. The MMT increased from 1997 to 2013 in all subgroups except for the
0–59 years age group and low socioeconomic status group. The annual MMT in Queensland and in different socioeconomic status groups during the study period is shown in table S1.

Sensitivity analyses showed that the effect estimates of temperatures did not change using 7, 14, and 21–28 lag days for temperature or 3–5 df for meteorological (figures S4–S6). The temperature-mortality associations in every five years (with three years overlapping) showed similar patterns as the pattern predicted using the time-varying DLNM model (figure S7). The exposure-response relationships between temperature and mortality for cardiovascular diseases in 1997 (blue) and 2013 (red) in 0–59 years age groups and in 35–59 years age groups showed similar trend (figure S8).
Figure 2. (A) The average overall cumulative exposure-response relationships between temperature and mortality for cardiovascular diseases between 1997 and 2013. (B) The overall cumulative exposure-response relationships between temperature and mortality for cardiovascular diseases in 1997 (blue) and 2013 (red).

Figure 3. (A) Temporal variations of the association between cold (1st percentile of temperature against MMT) temperature and mortality for cardiovascular diseases among different age, sex, climate zone and socioeconomic status groups between 1997 and 2013. (B) Temporal variations of the association between hot (99th percentile of temperature against MMT) temperature and mortality for cardiovascular diseases among different age, sex, climate zone and socioeconomic status groups between 1997 and 2013. Note: dotted line means RR equals 1.
Table 2. MMT (°C) for cardiovascular diseases among different subgroups between 1997 and 2013.

| Subgroups     | Overall | 1997  | 2013  |
|---------------|---------|-------|-------|
| Sex           |         |       |       |
| Male          | 24.2    | 21.2  | 24.5  |
| Female        | 23.0    | 23.0  | 23.0  |
| Age (years)   |         |       |       |
| 0–59          | 24.3    | 26.5  | 22.7  |
| 60–84         | 23.1    | 20.9  | 23.8  |
| 85+           | 23.5    | 23.0  | 25.2  |
| Climate       |         |       |       |
| Cold          | 23.8    | 23.0  | 25.3  |
| Mild          | 23.7    | 23.3  | 24.2  |
| Hot           | 22.1    | 20.0  | 23.3  |
| Socio-economic status |       |       |       |
| Low           | 23.5    | 33.1  | 23.1  |
| Middle        | 23.2    | 20.1  | 24.0  |
| High          | 23.6    | 23.3  | 33.1  |

4. Discussion

To our best knowledge, this is the first study to examine the temporal trend of temperature-cardiovascular mortality associations among different subgroups in subtropical-tropical climatic zones. We found substantial decrease in cold effect and minimal change in the heat effect between 1997 and 2013 in Queensland, Australia. In the subgroup analysis, our results demonstrated an obvious age-, sex-, geographic- and socioeconomic-specific pattern. For heat effect, the increased magnitude was higher in men than women and higher in people living in hot climate areas than those living in moderate and cold areas. People with high socioeconomic status and people ≥85 years old demonstrated adaptive capacity protecting them from the high temperatures.

The average effect of temperature on cardiovascular mortality during 1997 and 2013 was U-shaped, with cold effects larger than heat effect. The main thermoregulatory response to cold temperatures is peripheral vasoconstriction and shivering, mediated by sympathetic activation which may result in increased heart rate and blood pressure [22, 31, 32]. When exposing to high temperatures, peripheral vasodilatation and sweating are the main responses, which will cause increase in blood viscosity [33]. Similar to our findings, the stronger cold effect on cardiovascular mortality has been frequently reported in previous studies [8, 34]. One explanation is that individuals from warmer areas, such as Queensland, are more adapted to high temperatures, resulting in larger cold effect. However, Bunker et al systematically analysed the temperature-mortality associations for cardiovascular diseases in different locations and found that the overall heat effect [RR 1.034 (95%CI: 1.031, 1.040)] was stronger than cold effect [RR 1.017 (95%CI: 1.012, 1.021)] [35]. The different association patterns are probably due to the geographic variability, climatic variability or different humidity.

We observed a decrease in the cold effect from 1997 to 2013, whereas the heat effect showed no significant change for total cardiovascular diseases. A study in Shanghai, China had similar findings [6]. A study in London also demonstrated a progressive decline of cold-related cardiovascular mortality. However, studies in USA [20], Europe [17, 36], and Asia [21, 37] found the decline in heat-related mortality for cardiovascular diseases. The non-significant changes in the long-term heat-mortality associations in this study suggest that there was no adaptation to high temperatures in Queensland. Without effective adaptation, heat-related morality could increase up to 129% as the aging of population [38]. Therefore, urgent actions are needed to mitigate the impacts of high temperatures on people with cardiovascular diseases in Queensland, particularly in the context of temperature warming.

We found a decreasing heat vulnerability in colder climate zone and an increasing heat vulnerability in hotter climate zone. Previous studies demonstrated adaptive potential of individuals living in hotter environments [28]. However, our results indicated that this adaptation might have upper limits. People living in very hot areas cannot bear the increasing temperatures through adaptation. Additionally, in contrast to our findings, studies in Europe demonstrated a greater decrease in heat vulnerability in warmer cities [39, 40]. Our results demonstrated that local climate influenced trends in the associations between temperature and cardiovascular mortality. In Queensland, the hotter the place is the greater increase in heat vulnerability.

Cold effects showed a decreasing trend in all subgroups, except for 60–84 years age group. Heat effects increased in people ≤59 years and in the 60–84 years age group. Previous studies demonstrated the largest vulnerability decrease in the elderly group [18, 20, 41]. However, we found that people ≥85 years have adapted to ambient temperatures better than other age groups. The alleviated temperature-mortality associations would probably be induced by environmental factors, e.g. skilled senior caring facilities, improved heat/cold awareness, and air conditioning usage, and limited outdoor activities in the ≥85 years age group. In the era of global warming, adaptation to the extreme high temperatures can be realized with public health, education, or socioeconomic improvements.

The heat effect showed a non-significant decreasing trend in women and an increase in men. A study in Vienna, Austria investigated the heat-mortality associations between 1970 and 2007, finding that the heat vulnerability decreased more substantial in women than in men [38]. In this study, women had higher risks of cardiovascular mortality associated hot temperatures than men in 1997, which decreased to similar levels in 2013. However, the heat vulnerability for men continued to increase. Previous studies have reported that men are the vulnerable group to high temperatures [42, 43]. However, we cannot explore
the reason why heat-related cardiovascular diseases decreased in women and increased in men, as we do not have detailed information on their behavioural patterns and physiological characters. Further studies are needed to examine the potential determinants.

The magnitude of association between temperature and cardiovascular mortality decreased in high IRSAD areas. Consistently, a study in Japan found that people with improved annual income had a larger decrease of heat-related mortality between 1972 and 2010. Prefectures with improved economic strength had a greater reduction of heat-related mortality [37]. Chung et al. found an earlier decrease in vulnerability in Japan than Korea and Taiwan, China due to earlier development [44]. Poverty has been recognised as an independent effect modifier of the heat-mortality association [45, 46]. Our results confirmed these findings, whereby areas with socioeconomic advantages can mitigate the impacts of temperatures on cardiovascular mortality. Plausible explanations include higher education levels and risk awareness, in addition to greater access to air conditioning among people living in socioeconomic advantaged areas, leading to better adaptation to ambient temperature extremes.

This study has several strengths. First, we used mortality and weather data at the postcode level. It improves statistical accuracy of the associations between temperature and cardiovascular mortality. Secondly, we employed time-stratified case-crossover design to provide sufficient adjustments for confounders. This study provides additional evidence and significant insights for the adaptation to climate change at the population level.

There are some limitations. First, in this study, we did not control for wind velocity and air pollution due to the lack of data. Numerous studies have shown that the confounding effect of wind velocity and air pollution on the temperature-association hypothesis, if exist, should be limited [47–49]. However, this issue warrants further exploration on Australian population in the future when data will be available. Second, our exposure data is not at the personal level. We also did not examine the air conditioning usage in different areas of Queensland due to the unavailability of data. Finally, this study design cannot confirm causal associations.

5. Conclusions

The associations between cold temperature and cardiovascular mortality decreased in Queensland, Australia between 1997 and 2013, but no declines were observed for hot temperatures. Men, people aged 84 years old, people living in low and middle socioeconomic score areas and people living in hot climate areas even showed increased susceptibility to hot temperatures over the period. This worrying trend warrants targeted public health strategies to tackle heat-related cardiovascular mortality, especially in the context of global warming.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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