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Emergency department visits and associated healthcare costs
attributable to increasing temperature in the context of climate
change in Perth, Western Australia, 2012–2019

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Supplementary material for this article is available [online](#)

Abstract

Increasing temperature and its impact on population health is an emerging significant public health issue in the context of climate change in Australia. While previous studies have primarily focused on risk assessment, very few studies have evaluated heat-attributable emergency department (ED) visits and associated healthcare costs, or projected future health and economic burdens. This study used a distributed lag non-linear model to estimate heat attributable ED visits and associated healthcare costs from 13 hospitals in Perth, Western Australia, and to project the future healthcare costs in 2030s and 2050s under three climate change scenarios—Representative Concentration Pathways (RCPs) 2.6, RCP4.5 and RCP8.5. There were 3697 ED visits attributable to heat (temperatures above 20.5 °C) over the study period 2012–2019, accounting for 4.6% of the total ED visits. This resulted in AU\$ 2.9 million in heat-attributable healthcare costs. The number of ED visits projected to occur in the 2030s and 2050s ranges from 5707 to 9421 under different climate change scenarios, which would equate to AU\$ 4.6–7.6 million in heat associated healthcare costs. The heat attributable fraction for ED visits and associated healthcare costs would increase from 4.6% and 4.1% in 2010s to 5.0%–6.3% and 4.4%–5.6% in 2030s and 2050s, respectively. Future heat attributable ED visits and associated costs will increase in Perth due to climate change. Excess heat will generate a substantial population health challenge and economic burdens on the healthcare system if there is insufficient heat adaptation. It is vital to reduce greenhouse gas emissions, develop heat-related health interventions and optimize healthcare resources to mitigate the negative impact on the healthcare system and population health in the face of climate change.

1. Introduction

Climate change has emerged as one of the biggest public health challenges in this century [1]. The global average combined land and ocean surface temperature has increased by 0.85 °C due to rapid industrialization, urbanization and human activities over the period from 1880 to 2012 [2]. In 2014, the

Fifth Assessment Report of the Intergovernmental Panel on Climate Change Report predicted that the global average surface temperature will be further increased and the rise is likely to exceed 1.5 °C by the end of this century compared to 1850–1900 [2]. In addition, extreme weather events, e.g. hot temperature extremes, droughts, wildfires, floods and storms, will occur more frequently. In particular, increasing

temperatures are very likely to occur with a higher frequency and longer duration [2].

In Australia, the average surface air temperature has increased by 1.44 ± 0.24 °C since 1910 [3, 4], and by 2030, the Australian annual average temperature is projected to increase by 0.6 °C–1.3 °C under Representative Concentration Pathway (RCP) 4.5 compared with the climate of 1986–2005 [3]. The average temperature will be further increased by 2.8 °C–5.1 °C under a high greenhouse gas emissions scenario [3]. Australia is one of the developed countries most vulnerable to climate change due to its unique geographic character and climatic conditions, and all major cities are located in the coastal areas, which will be highly sensitive to the risks of climate change including the increasing temperature and sea-level rise [5].

Increasing temperatures could be associated with higher rates of temperature-related illnesses and diseases in the future, such as renal disease, heatstroke, cardiovascular disease, mental illness and respiratory disease [6–11]. A study in Adelaide, South Australia used hospital inpatient and emergency department (ED) admissions data from 2003 to 2014 and found increases in daily temperature were associated with an increased incidence in almost all renal disease categories [7]. Elsewhere, heatstroke and cardiovascular diseases have been associated with increasing ambient temperature [6, 8]. Mortality and morbidity due to mental illness and disorders and respiratory disease are also significantly associated with increases in ambient temperature in multiple countries [10, 12–16]. Additionally, a number of studies have shown that heatwaves or higher temperatures increase work-related injuries and illnesses [17–19]. Overall, studies in Australia have shown that increasing temperatures are associated with negative health impacts [11, 12, 20] including an increase in daily mortality [21].

The projected increase in temperatures in Australia will likely generate a greater heat-related burden to the healthcare system, including more ED visits and associated financial costs [3]. Although studies have examined the relationship between high temperature and temperature-sensitive diseases, most did not explore the number of cases and healthcare costs attributable to increasing temperatures, nor project the future burden of temperature-sensitive diseases and associated healthcare costs.

This study collected ED visit data and associated healthcare costs, and analyzed these against meteorological data, with the aim of examining the relationship between temperature-related cases, associated healthcare costs and temperature variation in Perth, Western Australia. Moreover, the future burden of temperature-related diseases due to climate change was also projected for the 2030s and 2050s. Findings from this study can be used to guide preparedness

planning and optimize future health services resource allocation in the region.

2. Methods

2.1. Study context

The study was conducted in Perth, the capital city of Western Australia, which is located on the coast in the southwest of Australia. The city's metropolitan area covers 6300 km² and its population was about 2.08 million in 2019 [22]. The city has a Mediterranean climate of hot and dry summers, cool and wet winters. A total of 13 Perth metropolitan hospitals, including public hospitals and public and private jointly operated hospitals, provide emergency care services in the area. The 13 hospitals are Royal Perth Hospital, Fremantle Hospital, Princess Margaret Hospital for Children, Sir Charles Gairdner Hospital, Fiona Stanley Hospital, King Edward Memorial Hospital for Women, Armadale-Kelmscott Memorial Hospital, Osborne Park Hospital, Rockingham General Hospital, Bentley Hospital, Murray District Hospital, Kalamunda District Community Hospital and Perth Children's Hospital. Patients from non-Perth metro area were excluded from the analysis. Three study periods were used: 2010s, 2030s and 2050s. The current baseline period of 2012–2019 was defined as 2010s; and projections for the corresponding periods 2032–2039 and 2052–2059 were defined as 2030s and 2050s, respectively.

2.2. Data sources

2.2.1. ED visits and costs

Daily ED visits to the 13 hospitals in the Perth metropolitan area and associated costs (in Australian dollars) for the study period from January 2012 to December 2019 were provided by the Western Australian Department of Health. The International Statistical Classification of Diseases and Related Health Problems, Tenth Revision, Australian Modification (ICD-10-AM) was used to identify diagnostic categories. Specifically, daily cause-specific ED visits including heat-related illnesses (ICD-10-AM: E86, T67, L55, X30), renal diseases (ICD-10-AM: N00–N39.9), ischemic heart diseases (ICD-10-AM: I20–I25), mental health disorders (ICD-10-AM: F00–F99.9), respiratory diseases (ICD-10-AM: J00–J99), and associated healthcare costs were used as the outcomes of interest in this study. These diseases have been shown to vary with temperature (either heat or cold) in Australia and other countries [6–11, 23–26]. The daily ED visits and associated healthcare costs for each of these individual disease categories were aggregated for statistical analysis, and defined as 'temperature-related disease ED visits' and associated healthcare costs; therefore, the outcome variables represented these combined cause-specific daily ED visits and associated healthcare costs in Perth.

2.2.2. Meteorological data

Daily mean temperatures (T_{mean}) for the study period 2012–2019 (2010s) were obtained from the Australian Bureau of Meteorology. It was the average of daily maximum temperature and minimum temperature. The centrally located weather observation station in Perth (Perth Metro Station ID: 009225) was selected to be representative of the Perth Metropolitan Area. Daily mean temperatures for the periods 2032–2039 (2030s) and 2052–2059 (2050s) were projected based on observed daily mean temperatures and the temperature change projected for Perth using three Commonwealth Scientific and Industrial Research Organisation (CSIRO)-defined RCPs. Based on greenhouse gas emission scenarios, these were RCP 2.6 (low), RCP 4.5 (medium) and RCP 8.5 (high) [27]. All temperature data were expressed as degrees Celsius.

2.2.3. Population data

Current population data for the period 2010s and projected populations for the periods 2030s and 2050s were obtained from the Australian Bureau of Statistics [22]. The population projection method considers a number of national and international trends including fertility, mortality, net overseas migration and net interstate migration. To simplify the analysis in this study, the estimated medium levels of fertility, life expectancy, net overseas migration and interstate flows were adopted. Daily population for the three study periods 2010s, 2030s and 2050s were estimated using linear interpolation [28].

2.3. Statistical analysis

The data analysis had two stages. First, the relationships between daily temperature-related ED visits, associated healthcare costs and daily mean temperatures were calculated for the period 2012–2019. Second, the future heat-attributable ED visits and costs were projected based on the current estimated associations and predicted temperature changes in Perth.

First stage: to assess the relationships with daily mean temperature, a generalized linear time series regression with a quasi-Poisson distribution was used for ED visits and associated healthcare costs. To assess the shape of the exposure–lag–response relationship, the distributed lag non-linear model (DLNM) was fitted simultaneously to estimate the possible non-linear relationship and delayed effects of temperature on ED visits and associated healthcare costs [29–31]. The model controlled for potential confounding effects of long-term trends, seasonality, weekday variations and public holidays. To control for long-term trends and seasonality, a natural cubic spline with seven degrees of freedom (df) per year for time was included in our analysis [32]. To control for weekday variations, the day of week (dow) was also included in the model. Public holidays (pubhol)

were controlled for using a binary variable (1 = public holiday; 0 = nonpublic holiday). The temperature-related effects were calculated in relation to the local reference temperatures, which was taken to be the temperature giving the lowest estimate in the cumulative exposure–response curves for ED visits and associated healthcare costs, as per the methods of Gasparri *et al* [30, 33]. Relative risk (RR) is associated with each temperature exposure level, compared with the local reference temperatures. We did not control for humidity in this analysis, as the weather is typically hot and dry during the warm season in Perth. To ensure the associated healthcare costs were comparable across years, consumer price index (CPI) data were obtained from the Australian Bureau of Statistics [34], and the daily associated healthcare costs were adjusted for inflation and standardized to the fourth quarter of 2019 in Australian dollars.

The models were described as follows:

$$Y_t \sim \text{Quasi-Poisson}(\mu_t) \text{ for ED visits/costs}$$

$$\begin{aligned} \log[E(Y_t)] = & \alpha + \text{cb}(T_{\text{mean}_t}) \\ & + \text{ns}(\text{time}, 7\text{df per year} \times 8 \text{ years}) \\ & + \text{dow}_t + \text{pubhol}_t \end{aligned}$$

where, Y_t is ED visits/costs on day t ; α is the intercept; $\text{cb}(T_{\text{mean}_t})$ is the cross-basis natural cubic spline function for daily mean temperature with both response and lag dimension applied from the DLNM; $\text{ns}(\text{time}, 7\text{df per year} \times 8 \text{ years})$ is the natural cubic spline with 7 degrees of freedom per year multiplied by 8 years study period, adjusted for the long-term trend and seasonality [32], the time is in days; dow_t is day of the week on day t with Sunday being the reference day; and pubhol_t is a binary variable representing public holidays on day t . Three internal knots were placed in the cross-basis natural cubic spline at 10th, 75th, and 90th percentiles across the range of temperatures (as these percentiles best represent the exposure–response relationship for projections of climate change impacts on health [35]). Additionally, three equally spaced knots were placed along the lag dimension. The two reference temperatures for ED visits and associated healthcare costs were identified via overall cumulative exposure–response curves in the first stage, and outcomes above the reference temperatures were assigned as heat effect, vice versa. A maximum lag of 28 days was used to completely capture the overall temperature-related ED visits and associated healthcare costs [32].

Second stage: the current exposure–response relationships between daily mean temperatures and outcomes (i.e. daily temperature-related ED visits and associated healthcare costs) were obtained from the first stage analyses and were used to estimate the effects of future projected temperature change on the outcome variables of interest [31]. The effects

of projected daily mean temperature on future temperature-related ED visits and associated healthcare costs were calculated for each day and summed for the study periods 2030s and 2050s for three future temperature scenarios (RCP2.6, RCP4.5, and RCP8.5). Heat-attributable effects were defined as all effects associated with temperatures above the reference temperatures. Heat attributable numbers (ANs) and attributable fractions (AFs) were calculated to show the number and percentage of ED visits and costs of the health outcomes associated with ambient temperature exposures. The AN and AF were calculated using a method of Gasparrini and Leone [36]. The AN and AF are defined as:

$$AN_{x,t} = AF_{x,t} \times N_t$$

$$AF_{x,t} = 1 - \exp \left(- \sum_{l=0}^L \beta_{x_{t-l},l} \right)$$

where x is the daily mean temperature exposure on day t ; N_t is daily ED visits/costs on day t . $\beta_{x_{t-l},l}$ is the natural logarithm of RR given exposure on day $t - l$ after l days have elapsed. In this study, we examined heat attributable visits and costs above the reference temperatures, which were identified via overall cumulative exposure–response curves in the first stage. For the future projection, the effects of projected daily mean temperatures above the current observed range were estimated using Monte Carlo simulation ($n = 1000$) [35, 36]. Empirical confidence intervals (95% CI) were also generated from the simulations to quantify the uncertainties in the exposure–response relationships. Projected ED visits and associated healthcare costs were also adjusted for the estimated future populations in 2030s and 2050s in the analysis.

Sensitivity analysis was conducted by changing the df for time from seven per year to five to nine per year, and the maximum lag days from 28 days to 21 days, to compare and best capture the effects of temperature on ED visits and associated healthcare costs. We also undertook sensitivity analysis using daily Tmean and daily 24 hour average of temperature (Mean24). Residual analysis and autocorrelation tests were conducted to evaluate the goodness of model fit and autocorrelation. All statistical analyses were performed using R software (version 4.0.1) with the packages ‘dlnm’, ‘tsModel’ and function ‘attrdl’ [36, 37], and Stata software (version 15.1) [38]. The statistical significance level of 0.05 was adopted for the analyses.

2.4. Ethics approval

This study obtained ethics approval from the Human Research Ethics Committee of the University of Adelaide (Approval No. ID33179) and the Department of Health WA Human Research Ethics Committee (Approval No. RGS0000001094).

3. Results

3.1. Descriptive analysis results

In the total of 2922 observation days, 79 899 temperature-related ED visits included 513 heat-related illnesses ED visits, 5409 ischemic heart diseases ED visits, 26 029 mental health disorders ED visits, 13 263 renal diseases ED visits and 34 685 respiratory diseases ED visits. These accounted for 15.8% of all 504 968 ED visits over the study period 2012–2019 in Perth. Of the 79 899, 41 100 ED visits were for males, and 38 799 were for females. The mean age was 40.7 (± 29.1 SD) years old. The details of characteristics for ED visits and costs in relation to temperature are shown in table 1. The mean of daily mean temperatures over the period was 19.2 (± 5.1 SD) °C with a range between 8.2 °C and 35.4 °C. The daily number of temperature-related ED visits ranged from 11 to 54 with a mean of 27 (± 6 SD). The daily minimum, mean, and maximum ED costs were AU\$7845, AU\$25 024, and AU\$ 51 604, respectively.

Three different RCPs were used to project future temperatures increases in Perth for the period 2030s and 2050s (see supplementary figure S1 (available online at stacks.iop.org/ERL/16/065011/mmedia)). The mean temperature is projected to increase 0.8 °C, 0.9 °C and 1.0 °C in 2030s under RCP2.6, RCP4.5 and RCP8.5 in Perth, compared to the reference period 1986–2005; and for the period 2050s the mean temperature will increase 0.9 °C, 1.3 °C, and 1.8 °C under RCP2.6, RCP4.5 and RCP8.5, respectively (supplementary table S1). The current daily mean temperature (2012–2019) in Perth increased by 0.48 °C relative to the climate reference period 1986–2005, based on our calculation.

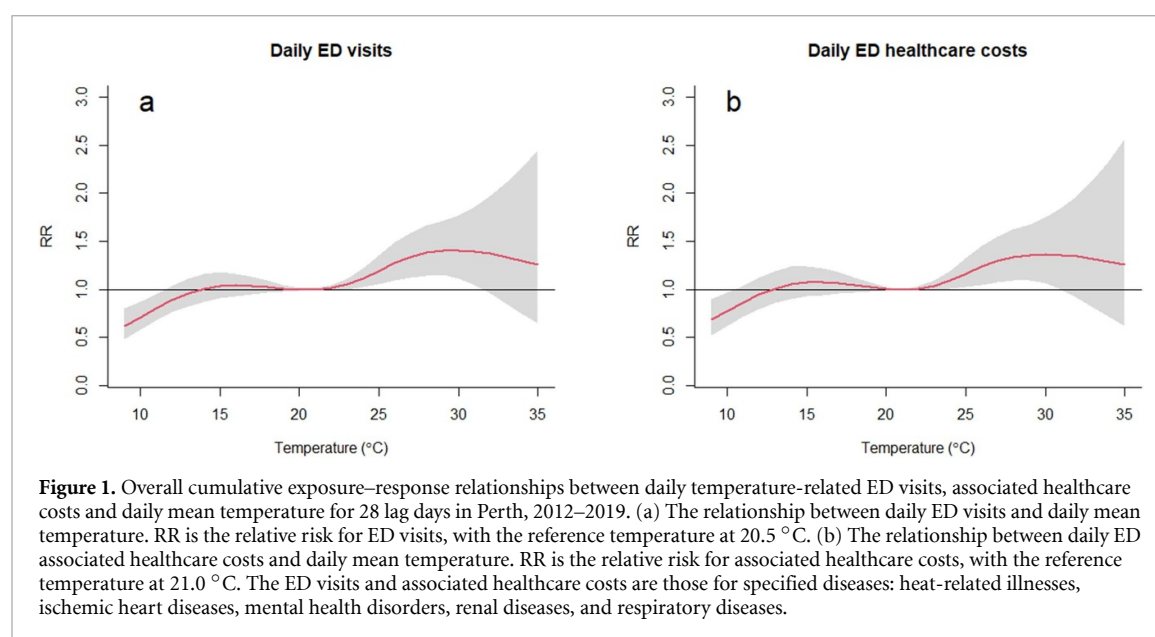
3.2. Exposure–lag–response relationships between temperature-related ED visits, associated healthcare costs and temperature

The overall cumulative exposure–response relationships between ED visits and daily mean temperature are shown in figure 1(a). The reference temperature of 20.5 °C was identified for temperature-related ED visits (figure 1(a)). We found that overall temperature-related ED visits increased with increasing heat exposure. The exposure–lag–response relationships between daily ED visits and daily mean temperatures are presented in figure 2. In particular, the RR of heat exposure for daily heat-related illness ED visits, mental health disorder ED visits and respiratory disease ED visits are the highest at 0 day lag (figure 3). Further, the heat effect on mental health disorders could last for three to four weeks, while there are no apparent effects for other diseases beyond lag one day (supplementary figures S2–S7).

The overall cumulative exposure–response relationships between ED healthcare costs and daily mean

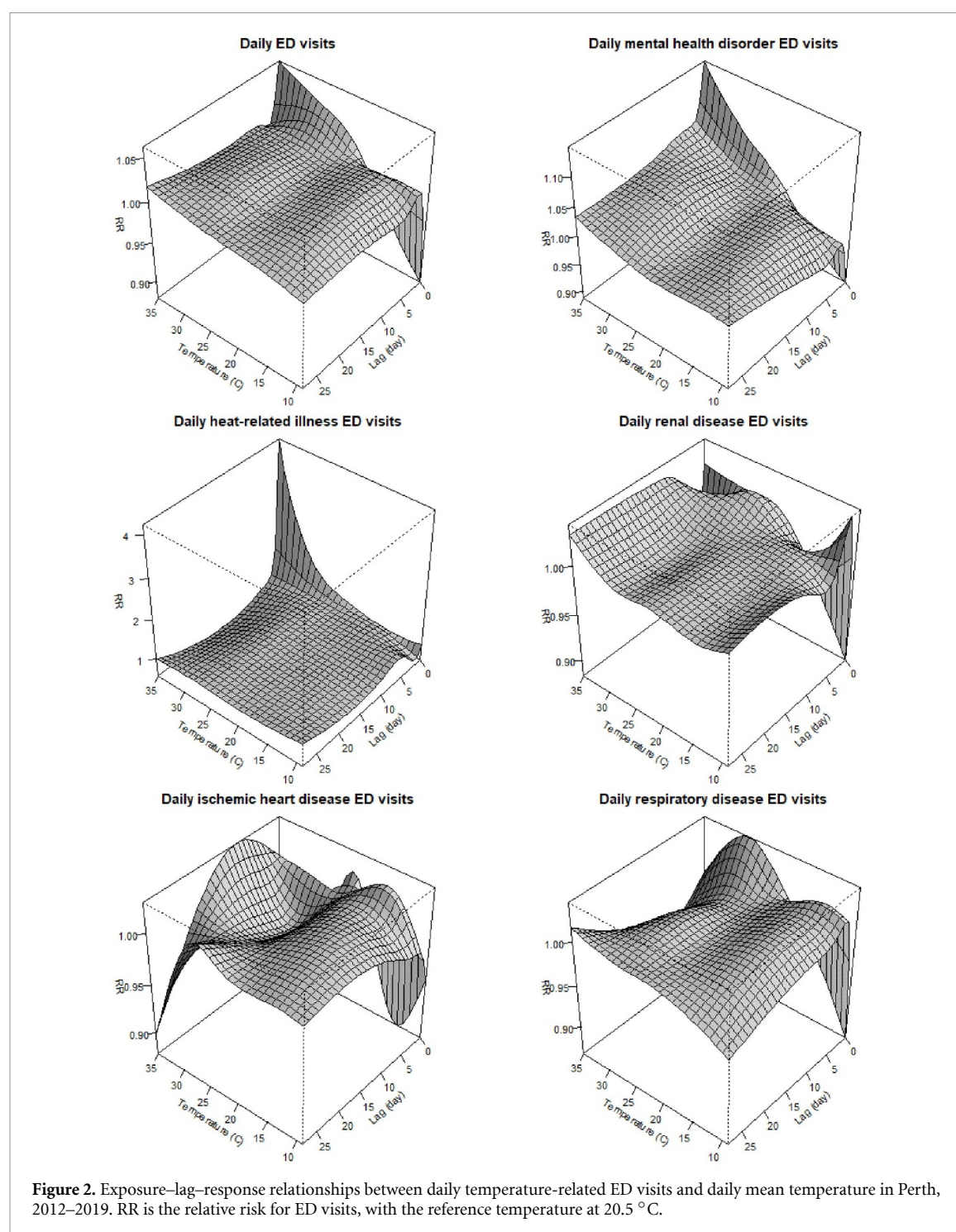
Table 1. Characteristics of emergency department visits and costs for temperature-related diseases in Perth, 2012–2019.

Characteristics	Number of ED visits (N)	Percentage (%)	Cost of ED visits (AU\$)	Percentage (%)
Gender				
Male	41 100	51.4	37 667 326	51.5
Female	38 799	48.6	35 452 645	48.5
Age group (years)				
0–9	16 848	21.1	10 438 839	14.3
10–17	3970	5.0	3256 121	4.5
18–24	6894	8.6	6043 815	8.3
25–34	9075	11.4	8102 902	11.1
35–44	8132	10.2	7501 540	10.3
45–54	7344	9.2	7115 379	9.7
55–64	6928	8.7	7145 360	9.8
65–74	6687	8.4	7314 813	10.0
75+	14 021	17.5	16 201 203	22.2
Diseases				
Heat-related illnesses	513	0.6	470 462	0.6
Ischemic heart diseases	5409	6.8	6892 452	9.4
Mental health disorders	26 029	32.6	24 575 897	33.6
Renal diseases	13 263	16.6	12 468 736	17.1
Respiratory diseases	34 685	43.4	28 712 424	39.3
Total	79 899	100	73 119 971	100



temperature are shown in figure 1(b). The reference temperature of 21.0 °C was identified for ED healthcare costs (figure 1(b)). A similar increasing trend can be found between ED healthcare costs and heat exposure. Figure 4 shows the exposure–lag–response relationships between daily ED healthcare costs and daily mean temperatures. The daily ED healthcare costs increased immediately (lag 0–1 day) after heat exposure except for the ischemic heart disease and renal disease ED costs (figure 5). Lastly, we found that cold exposure at lag 0 was associated with a reduced number of ED visits and associated healthcare costs (figures 3 and 5).

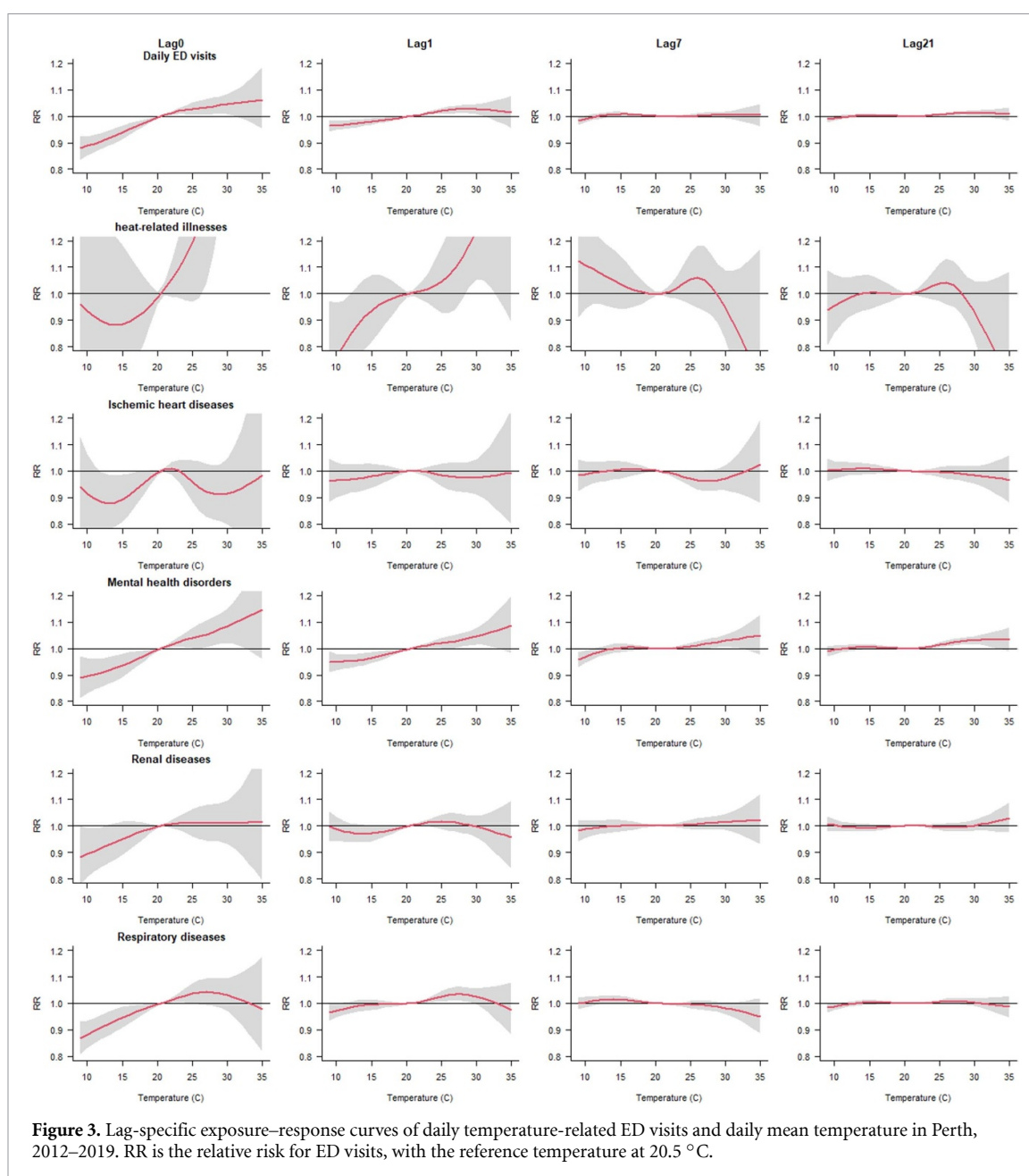
The total temperature-related ED visits and associated healthcare costs attributable to heat (i.e. that occur above the reference temperatures) are presented in table 2. Of the total 79 899 ED visits, heat attributable ED visits comprised 3697 visits, which accounted for 4.6% of the total. The ED associated healthcare costs due to heat were AU\$2975 215 over the study period 2012–2019, accounting for 4.1% of the total \$73 119 971 ED healthcare costs. In addition, we also examined the cold effect on temperature-related ED visits, and the cold attributable ED visits (i.e. below the reference temperatures) and associated healthcare costs are presented in supplementary table S2.



3.3. Projected temperature increases and the effect on ED visits and associated healthcare costs

Projected heat-attributable ED visits and associated healthcare costs for the three different RCP scenarios in 2030s and 2050s are shown in table 2. In 2030s, the heat-attributable ED visits could be increased from 3697 in 2010s to 5707; 5847 and 5989 under the RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively. In 2050s, the heat attributable ED visits could be further increased to 7694; 8447 and 9421 under RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively. Correspondingly, the heat AF of ED visits will increase

from 4.6% in 2010s to 5.0%, 5.1% and 5.3% in 2030s, to 5.1%, 5.6% and 6.3% in 2050s under the RCP2.6, RCP4.5 and RCP8.5, respectively. In particular, the ED visit associated healthcare costs will increase from AU\$2975 215 to AU\$ 4841 464 under RCP8.5 in 2030s and AU\$ 7649 145 under RCP8.5 in 2050s, which would account for 4.6% and 5.6% of the ED healthcare costs in 2030s and 2050s, respectively. In addition, cold-attributable ED visits and associated healthcare costs are projected over the period 2030s and 2050s (supplementary table S2). However, no significant changes in the effect of cold



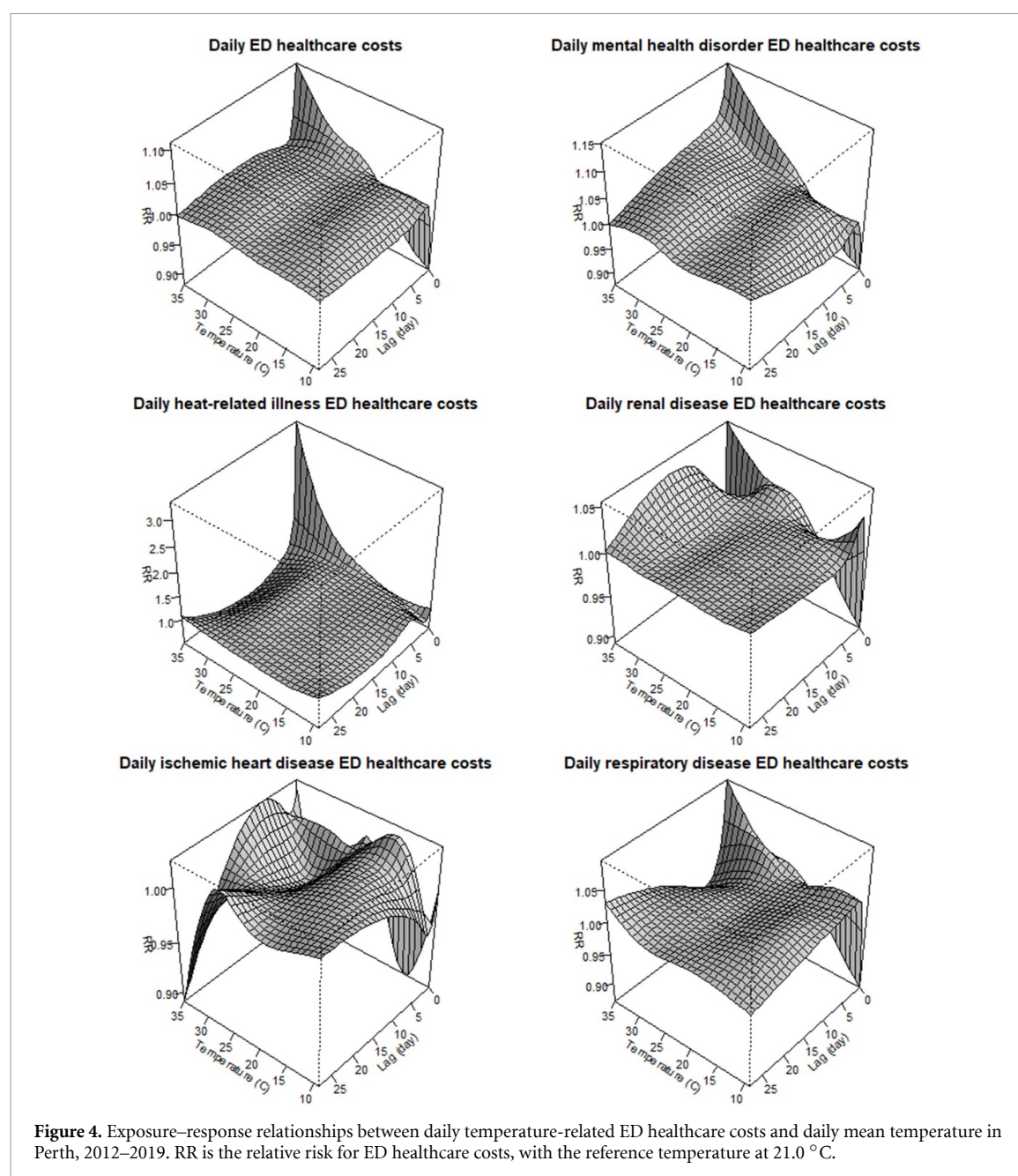
exposure on ED visits and associated healthcare costs were found.

3.4. Sensitivity analysis

Sensitivity analyses were conducted to evaluate the performance of the models. The association between daily mean temperature, daily ED visits and associated healthcare costs were consistent when changing the df of the natural cubic spline for the calendar year from 7 to 5–9 (supplementary figure S8), changing the maximum lag days from 28 days to 21 days (supplementary figure S9), and changing daily T_{mean} to Mean24 (supplementary figure S10). The residuals for the DLNM models followed a normal distribution, and autocorrelations were controlled after including the first-order lagged variable of the residuals (supplementary figures S11 and S12).

4. Discussion

The impact of climate change on human health has been studied extensively due to the increased extremely hot days. With respect to the assessment of heat-attributable health and economic burden, many studies have tended to concentrate on the effect of ambient temperature on the healthcare costs of hospital admissions only [39, 40]. While it should be noted that hospital admissions capture severe health outcomes, ED visits data may more widely reflect morbidity of temperature-related illnesses and the health burden to population health and the healthcare system. Further exploration of the relationship between high temperatures and ED visits, and associated healthcare costs could make a vital contribution to a better understanding of the total public



health impact of climate change on the healthcare system.

Although a previous study has shown hot temperature and heatwaves increase daily ED visits in Perth [21], no study has examined the associated healthcare costs in this region. To the best of our knowledge, this study is the first to explore the effect of ambient temperature on ED associated healthcare costs in Perth, and very few internationally to predict the future health and economic burden for the 2030s and 2050s in this region. We quantified the projected temperature-related ED visits and healthcare costs under three RCP scenarios with the consideration of population change. Our results demonstrated that higher temperature contributed to an increasing burden of adverse health outcomes and associated healthcare costs in Perth for the current and for the future

period of 2030s and 2050s. In particular, under the scenario of greenhouse gas emission of RCP8.5, there is a substantial increasing burden on the ED visits from 3697 visits across eight years in 2010s, to 9421 visits in 2050s, and associated healthcare costs from AU\$ 2.9 million in 2010s to AU\$ 7.6 million in 2050s, suggesting there could be an additional 157% increase in the associated healthcare costs in the middle of this century, although the CIs were wide.

In this study, we found there was a non-linear relationship between temperature and ED visits with immediate and lagged effects. This could be due to certain heat effects occurring immediately (lag 0–1 day) for ED visits, such as heat-related illnesses, mental health disorders and respiratory diseases, while simultaneously, the heat effects lasted for three to four weeks for mental health disorders.

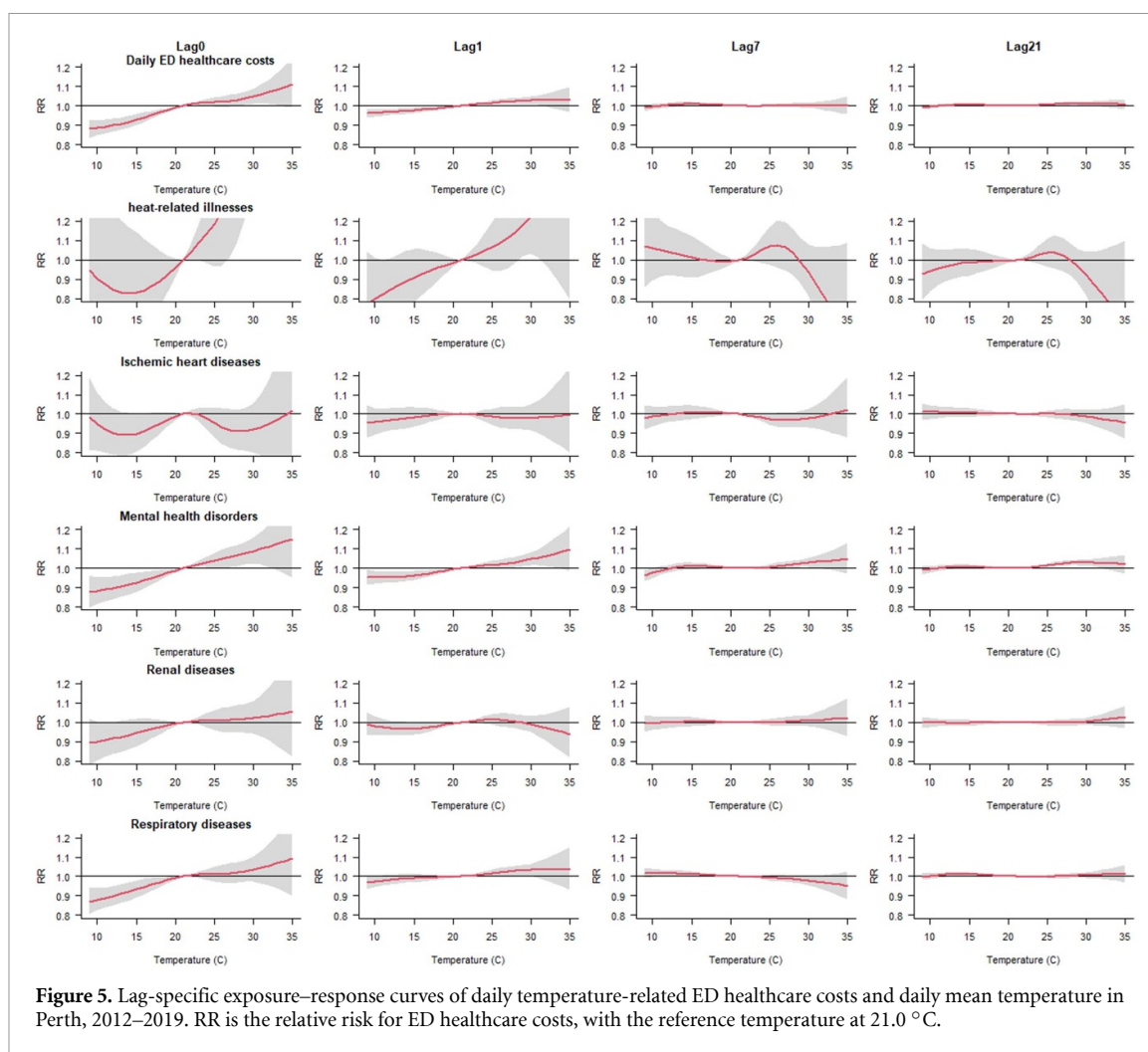


Figure 5. Lag-specific exposure–response curves of daily temperature-related ED healthcare costs and daily mean temperature in Perth, 2012–2019. RR is the relative risk for ED healthcare costs, with the reference temperature at 21.0 °C.

Table 2. Total heat-attributable ED visits (*N*) and associated healthcare costs (AU\$) in Perth for 2012–2019 (2010s), and projection for 2032–2039 (2030s) and 2052–2059 (2050s).

Period	Heat attributable number		Heat attributable fraction (%)	
	ED visits (95% CI)	Associated costs AU\$ (95% CI)	ED visits (95% CI)	Associated costs (95% CI)
2010s				
Current	3697 (1529; 5744)	2975 215 (850 234; 4881 984)	4.63 (1.91; 7.19)	4.07 (1.16; 6.68)
2030s				
RCP2.6	5707 (2381; 8826)	4606 748 (1365 864; 7486 088)	5.01 (2.09; 7.74)	4.42 (1.31; 7.18)
RCP4.5	5847 (2437; 9037)	4723 524 (1420 513; 7661 541)	5.13 (2.14; 7.93)	4.53 (1.36 7.35)
RCP8.5	5989 (2508; 9239)	4841 464 (1476 887; 7838 552)	5.25 (2.20; 8.11)	4.64 (1.42; 7.52)
2050s				
RCP2.6	7694 (3203; 11 895)	6204 365 (1862 020; 10 069 357)	5.14 (2.14; 7.94)	4.53 (1.36; 7.35)
RCP4.5	8447 (3581; 13 035)	6832 832 (2123 267; 11 045 840)	5.64 (2.39; 8.71)	4.99 (1.55; 8.06)
RCP8.5	9421 (4106; 14 489)	7649 145 (2318 785; 12 220 514)	6.29 (2.74; 9.68)	5.58 (1.69; 8.92)

This is consistent with other studies that indicated the positive association between temperatures and heat-related illnesses, mental health disorders and respiratory diseases [21, 25, 26, 41]. In this study, we did not find significant heat effects on ischemic heart diseases and renal diseases. This could be due to the severity of the two diseases, and patients might be more likely to receive hospital inpatient care directly [32, 42]. Previous studies also observed no associations between the effect of high ambient temperatures on cardiovascular conditions including ischemic heart diseases in the

ED visits [26, 43, 44]. However, some other studies have found a positive relationship between temperature increase and renal diseases in ED visits [7, 21, 26].

The reference temperatures of 20.5 °C for ED visits and 21.0 °C for ED costs were chosen based on the overall cumulative exposure–response curves in this study. The results are consistent with studies in China and United States, which found similar non-linear relationships between temperatures and ED visits/costs with reference temperatures of 17.7 °C in China and 21.6 °C in United States [32, 45]. In

addition, we found the ED visits were significantly fewer and associated healthcare costs were less when the temperature was below 10 °C at lag 0 day. This could be due to the sudden temperature drop that discourages outdoor activities, so that there are fewer ED visits at lag 0 day, while the ‘protective’ effect of cold would be mitigated after one day lag.

Heat attributable ED visits accounted for 4.6% (3697 visits) of total ED visits of the selected disease categories in Perth within the study period. This accounted for 4.1% of total ED visit associated healthcare costs, estimated to be AU\$2.9 million for the study period of 2010s. Thus, each year on average, there are 462 heat attributable ED visits, from the population of 2.08 million, costing AU\$ 371 902 per year, with an average cost for each individual visit of AU\$805 in Perth. Toloo *et al* conducted a study in Brisbane (population 2.5 million) that indicated costs of excess ED visits were AU\$40 876 per year for 2012–2013 [24]. Some of these differences could be due to different meteorological factors used, the different population characteristics, geographical features, climate conditions or heat adaptations in these regions. For example, the dry climates of Perth differ from the humid subtropical climate in Brisbane [46]. In addition to the weather, although Perth has a smaller population compared with Brisbane, the Perth population has an older median age than Brisbane [47], that may be more vulnerable to higher temperatures and heatwaves [48, 49]. This could account for the higher temperature-related ED visits and associated healthcare costs in Perth.

For the future projections of heat-attributable ED visits and costs, the overall heat AF for the ED visits increased by 0.4%–1.7% from 4.6% in 2010s to between 5.0% (RCP 2.6) in 2030s and 6.3% (RCP 8.5) in 2050s; and associated healthcare costs increased by 0.3%–1.5% from 4.1% in 2010s to 4.4%–5.6% in 2030s and 2050s, respectively. However, this will lead to at least a 54.4% increase in the number of ED visits and 54.8% increase in the associated healthcare costs under the RCP 2.6 in 2030s, compared with ED visits and associated costs in 2010s. Whilst for the RCP 4.5 and RCP 8.5, this implies the number of heat-attributable ED visits will increase by 58.2% and 62.0% in 2030s, associated healthcare costs will increase by 58.8% and 62.7%, respectively, relative to the current heat-attributable ED visits and associated healthcare costs. The heat-attributable ED visits and associated healthcare costs will be further increased by 154.8% and 157.1% under RCP 8.5 in 2050s, relative to the current heat-attributable ED visits and costs in 2010s. This is in line with another study conducted in Melbourne, which showed the overall cost of heat impacts on health would increase significantly from AU\$26.9 million in 2012 to AU\$77.0 million in 2030 and AU\$116.2 million in 2050 [50]. Comparable results have been reported in another study conducted in Australia, which predicted a substantial increase in

heat-related ED visits and associated healthcare costs in Brisbane for the future of 2060s [24]. Other studies in Australia and the US implied the similar trend of ED utilization when temperature increased [51–53]. From the standpoint of prevention, such clear evidence in Australia and worldwide suggests that effective and urgent climate mitigation would reduce the negative impacts on population health and healthcare systems, in particular for the short-term immediate heat effects on heat-related illnesses and respiratory diseases, and lagged heat effect on mental health disorders. Future studies could focus on the changing patterns of these diseases in the context of climate change to use the ED services. These studies will further specify the details in the policymaking for health resources allocation, health professional capacity building, climate change adaptation strategies and mitigation measures. In addition, further exploration of cardiovascular conditions and renal diseases in hospital admissions of Perth would give a full picture of the effect of temperature on human health.

With respect to the limitations of this study, four should be acknowledged. First, we assumed the current exposure–response relationships between daily mean temperatures and outcomes will be steady in the future, and no adaptation will be implemented to the changing climate. Second, although this study considered the different climate and population change scenarios for the future projections, other factors could also alter the outcomes of the projections, such as disease outbreaks, air pollution exposures, socioeconomic development, work and lifestyle changes, and new government policies on climate change. For example, recent COVID-19 epidemic may disrupt population migration and reduce future population growth. Such changes may also have implications for healthcare costs associated with both climate and population change, in particular, an aging population may be more vulnerable to temperatures due to diminished thermoregulatory ability [54]. The generalizability of this study to other regions should be cautious with the consideration of local demographics and climate conditions. Third, our ED data were from 13 public hospitals and private jointly operated hospitals in Perth, which may not cover all ED visits in this region. Therefore, the overall ED visits and associated healthcare costs are likely to be underestimated. Last, the healthcare costs were based on the CPI in the fourth quarter of 2019, and may not reflect the future healthcare costs due to the inflation, advancement of medical technologies, pharmaceutical manufacturing and drug development.

5. Conclusion

It is most likely that the heat AF of ED visits and associated costs will be increased from 4.6% and 4.1% in 2010s to 5.1% and 4.5% under RCP2.6, 5.6% and

5.0% under RCP4.5, 6.3% and 5.6% under RCP8.5, respectively by the midcentury in Perth due to climate change, unless appropriate climate change and adaptation strategies and measures are implemented. This will generate a substantial disease and economic burden on the healthcare system, in particular for heat-related illnesses, respiratory diseases, and mental health disorders. It is vital for government agencies, hospitals and other relevant stakeholders including local community members and health workers to work closely together to reduce the likely increasing number of heat attributable illnesses in the future and mitigate the impact on population health and the healthcare system in the face of climate change.

Data availability statement

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

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Author contributions

M T analyzed and interpreted the data, and drafted the manuscript. B W and K D assisted with the data analysis. J X, S W, A H, K D, J X, H B and P B revised and edited the manuscript. All authors reviewed the document and contributed to the final version of the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

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