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The impact of summer temperatures and heatwaves on mortality and morbidity in Perth, Australia 1994–2008

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ABSTRACT

Climate change projections have drawn attention to the risks of extreme heat and the importance of public health interventions to minimise the impact. The city of Perth, Western Australia, frequently experiences hot summer conditions, with recent summers showing above average temperatures. Daily maximum and minimum temperatures, mortality, emergency department (ED) presentations and hospital admissions data were acquired for Perth for the period 1994 to 2008. Using an observed/expected analysis, the temperature thresholds for mortality were estimated at 34–36 °C (maximum) and 20 °C (minimum). Generalised estimating equations (GEEs) were used to estimate the percentage increase in mortality and morbidity outcomes with a 10 °C increment in temperature, with adjustment for air pollutants. Effect estimates are reported as incidence rate ratios (IRRs). The health impact of heatwave days (three or more days of ≥35 °C) was also investigated. A 9.8% increase in daily mortality (IRR 1.098; 95%CI: 1.007–1.196) was associated with a 10 °C increase in maximum temperature above threshold. Total ED presentations increased by 4.4% (IRR 1.044; 95%CI: 1.033–1.054) and renal-related ED presentations by 10.2% (IRR 1.102; 95%CI: 1.071–1.135) per 10 °C increase in maximum temperature. Heatwave days were associated with increases in daily mortality and ED presentations, while total hospital admissions were decreased on heatwave days. Public health interventions will be increasingly important to minimise the adverse health impacts of hot weather in Perth, particularly if the recent trend of rising average temperatures and more hot days continues as projected.

1. Introduction

Most Australian cities experience hot days and occasional heatwaves throughout summer; and these conditions have been associated with increased mortality or morbidity, particularly for mental and behavioural, renal, cardiovascular, respiratory or cerebrovascular outcomes (Bi et al., 2011; Khalaj et al., 2010; Loughnan et al., 2010b; Nicholls et al., 2008; Tong et al., 2010a; Tong et al., 2010b; Vaneckova et al., 2008a; Vaneckova et al., 2008b). Climate change is projected to increase the frequency, intensity and duration of heat events across regions of Australia (CSIRO, 2007), and the need for public health planning to minimise the adverse health impacts of these events is now well recognised. The diversity of climatic conditions across Australia means that local evidence relating health outcomes to temperature is required for extreme heat planning. The relationship between temperature and mortality typically exhibits a U- or J-shaped curve, with a location specific heat threshold above which mortality increases. Heat threshold temperatures have been estimated for a number of Australian cities (Bambrick et al., 2008; Gosling et al., 2007; Guest et al., 1999; Loughnan et al., 2010a; Nicholls et al., 2008; Tong et al., 2010b; Vaneckova et al., 2008a), and in some cases these thresholds have been incorporated into heat-health action plans (Government of Victoria, Department of Health, 2009).

Perth is located in the temperate south-west of Australia, and is the fourth most populous city, with an estimated population of 1,659,000 (Australian Bureau of Statistics, 2011). Compared with other major cities in Australia, Perth experiences high summer temperatures, with the mean maximum temperature during the summer months of January and February exceeding 30 °C (Australian Bureau of Meteorology, 2011a). However, on most summer afternoons a sea breeze, known as "The Fremantle Doctor", blows from the south-west, providing relief from hot north-easterly winds. Recent summers in Perth have recorded

Abbreviations: ED, emergency department; GEE, generalised estimating equation; O_3, ozone; NO_2, nitrogen dioxide; $PM_{2.5}$, particulate matter of mass median aerodynamic diameter <2.5 μm; ppb, parts per billion; IRR, incidence rate ratio.

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higher than average maximum temperatures and numbers of hot days (>30 °C and >35 °C) (Australian Bureau of Meteorology, 2011b). A heatwave policy for Perth has recently been developed (Government of Western Australia, Department of Health, 2010), however there is limited research relating health outcomes to temperature for this population. Guest et al. (1999) estimated temperature-attributable mortality in five Australian cities, and concluded that climate had no apparent impact on mortality in Perth. In contrast, Bambrick et al. (2008) examined temperature-related mortality for Perth and Western Australia and projected an increase in temperature-related deaths by 2070 in response to unmitigated climate change.

Climate projections for the city of Perth include an increase in the number of hot days (≥35 °C) from an annual average of 28 (at Perth Airport) to over 50 days in 2070, under a high emissions scenario (CSIRO, 2007). Maloney and Forbes (2011) have projected that the number of days when hyperthermia is likely to develop will markedly increase, having important consequences for work and leisure activities.

The purpose of this study was to examine the relationships between high temperatures and adverse health outcomes for the population of Perth and to identify specific health outcomes that are sensitive to extreme heat. Evidence of these relationships can contribute to public health planning for extreme heat for this population.

2. Materials and methods

2.1. Health and meteorological data

Daily all-cause mortality (1 January 1983–30 November 2006), hospital admissions (1 January 1980–1 July 2008) and emergency department (ED) presentations (1 January 2002–30 April 2009) data were acquired from the Government of Western Australia, Department of Health. Hospital admissions data were from public and private hospitals in the Perth metropolitan area, and included emergency and elective admissions. Data for ED presentations were from metropolitan public and private hospitals. For hospital admissions and ED presentations, the following international classifications of diseases (ICD, revisions 9 and 10) were used: mental (ICD-9, 290–294.9; ICD-10, F00-F99), renal (ICD-9, 580–599.9; ICD-10, N00-N39), total cardiovascular (ICD-9, 390–459.9; ICD-10, I00-I99), respiratory (ICD-9, 460–519.9; ICD-10, J00-J99).

Daily weather data were provided by the Australian Bureau of Meteorology (BOM). Variables included daily maximum and minimum temperatures (°C) from the Perth Airport station (BOM station number 009021; WMO index number 94610), for the period 1 January 1980 to 3 April 2009; and from the Perth Metro station (BOM station number 009225; WMO index number 94608), located at Mount Lawley, for the period 12 January 1994 to 30 April 2011. Air quality data for ozone (O_3, maximum 1 hourly in ppb), nitrogen dioxide (NO_2, maximum 1 hourly in ppb), and particulate matter of mass median aerodynamic diameter <2.5 μm ($PM_{2.5}$, 24 hour mean in $\mu g/m^3$) were provided by the Department of Environment and Conservation, Western Australia. Air quality data were averaged for three metropolitan sites (Duncraig, Caversham, Swanbourne), subject to availability, for the period 1 March 1994–31 December 2008.

2.2. Statistical analyses

All analyses were conducted in StataIC10 (StataCorp. College Station, TX). Estimation of mortality heat thresholds used an observed/expected analysis, following the method of Dessai (2002). A 31-day moving average, including 15 days before and after the index day, was used to provide an estimate of expected daily mortality. Daily excess mortality was calculated by subtracting the expected values from the observed daily values. To relate excess mortality to daily temperatures, days were grouped into 1 °C or 2 °C intervals of daily maximum or minimum temperature after rounding to the nearest whole degree, and mean daily excess mortality was calculated for each temperature interval. Using 2 °C intervals reduced the resolution at which thresholds could be identified, but helped to smooth the high variability in daily mortality at higher temperatures, where the number of days in each group were limited. The heat threshold is defined as the temperature interval below which excess events are not discernible (Dessai, 2002).

To analyse mortality and morbidity outcomes in relation to temperature, including ED presentations and hospital admissions, we used generalised estimating equations (GEEs) (Diggle et al., 1994). Only the warmer months, 1 November through 30 April were considered in the analysis. A negative binomial distribution was assumed for mortality and morbidity outcomes, including hospital admissions (total) and ED presentations (total, mental, renal, cardiovascular and respiratory). We assumed independence between successive warm seasons and specified a first-order autoregressive structure to account for the correlation of daily outcomes within each warm season, as observed in other studies (Baccini et al., 2008; Fouillet et al., 2007). Models took into account the following potential confounders: day of the week, month, year, O_3, NO_2, and $PM_{2.5}$. The pairwise Pearson correlation coefficients for the different air pollution terms ranged from 0.34 to 0.49, thus multicollinearity was not a major concern. The effect of temperature was estimated as the percent increase in daily mortality or morbidity in relation to a 10 °C increment, or during heatwave compared to non-heatwave days. Effect estimates were expressed as incidence rate ratios (IRRs). The temperature predictors used were: (i) temperature (maximum or minimum) minus threshold for mortality, set as 0 if temperature <threshold; (ii) daily maximum and minimum temperature for all other outcomes; and (iii) a categorical variable defining heatwave and non-heatwave days. Heatwaves were defined using the Australian Bureau of Meteorology (Western Australia) definition of three or more days of 35.0 °C or above, measured at Perth Metro station (Australian Bureau of Meteorology, 2011b). The periods of data analysed in GEE models were: 1 March 1994 to 30 November 2006 (mortality); 1 January 2002 to 30 December 2008 (ED presentations); and 1 March 1994 to 30 April 2008 (hospital admissions). One day was omitted due to missing $PM_{2.5}$ data.

We used the estimated mortality threshold and dose–response relationship to estimate annual heat-attributable mortality for warm seasons following the approach used by McMichael et al. (2003) and Guest et al. (1999).

3. Results

3.1. Temperature thresholds for mortality

As a preliminary investigation the relationships between mean daily mortality and daily temperatures were examined using scatter plots (Fig. 1). These plots suggest a J-or U-shaped relationship between mean daily mortality and daily maximum or minimum temperatures, with a zone of comfort between 25 and 40 °C for maximum temperature and 15 and 25 °C for minimum temperature. The days contributing to the two apparent outliers on these plots were closely examined and mortality on these days did not lie outside the normal range.

Estimates for heat thresholds for mortality were made using an observed/expected analysis because it accounts for time and seasonal trends in the data. Fig. 2 shows plots of mean excess daily mortality against 2 °C intervals of daily maximum and minimum temperatures. Maximum and minimum temperature heat thresholds of 34–36 °C and 20 °C, respectively were estimated for the Perth population. The same estimates were obtained whether temperature data from Perth Airport or Perth Metro stations were used.

3.2. Daily mortality and morbidity in relation to maximum and minimum temperatures

Table 1 summarises the associations between daily temperatures and different health outcomes estimated using GEEs. Results are shown for maximum and minimum temperature variables, with and without adjustment for the effects of O_3, NO_2 and $PM_{2.5}$. The increase in the standard errors of the coefficients for temperature variables in adjusted compared with unadjusted models was less than two-fold in all cases. This was taken as evidence that multicollinearity was not a major issue. A significant association between daily mortality and temperature was observed when adjusted for air pollutants, with a 9.8% increase (IRR 1.098, 95% CI 1.007–1.196) in daily deaths associated with a 10 °C increase in maximum temperature above threshold, and a 27.9% increase in daily mortality (IRR 1.279, 95% CI 1.093–1.497) associated with a 10 °C increase in minimum temperature over threshold. From Fig. 1 it appeared that the effect of temperature on mortality may be amplified at extremes. Therefore

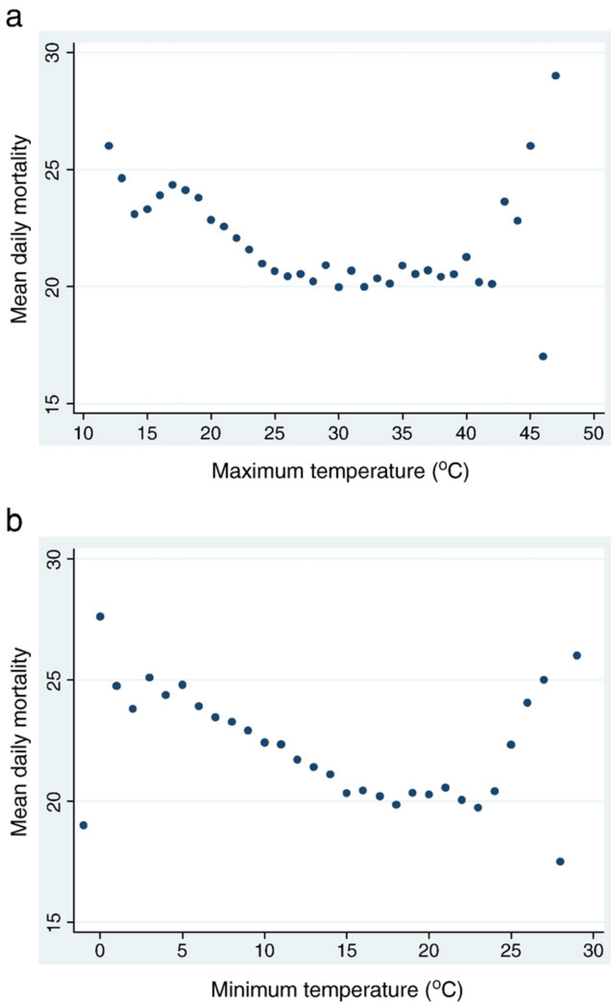

Fig. 1. Mean daily mortality in relation to daily (a) maximum and (b) minimum temperatures, in Perth, Western Australia. Plots represent data from 1 January 1983 to 30 November 2006.

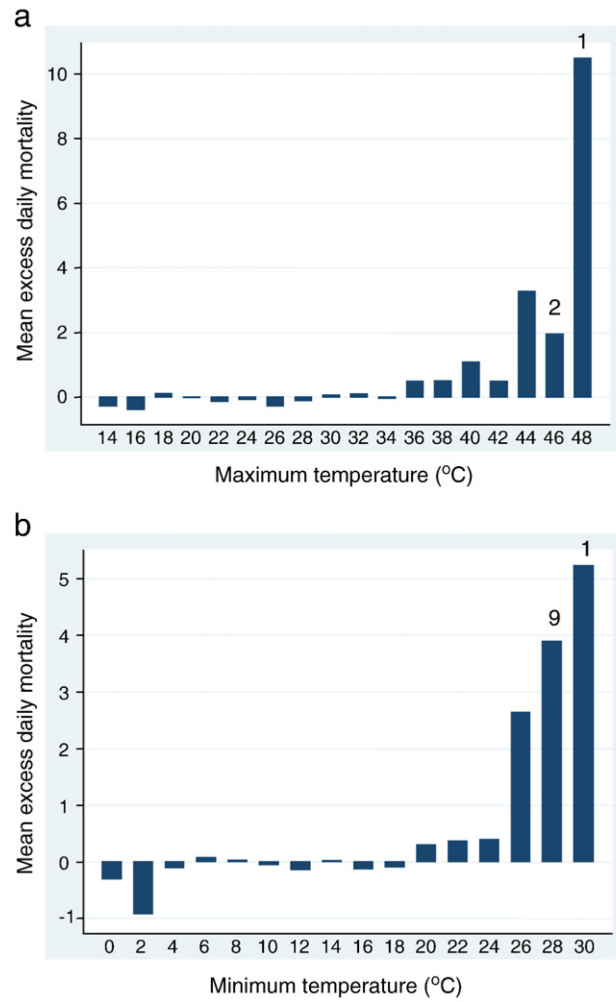

Fig. 2. Mean excess daily mortality associated with daily (a) maximum and (b) minimum temperatures, in Perth, Western Australia. Plots represent data from 1 January 1983 to 30 November 2006. The number of days contributing to the temperature interval is shown if less than 10.

we also estimated effects for maximum temperatures over a 40 °C cut-off and for minimum temperatures over 24 °C. Per 1 °C increase in maximum temperature over 40 °C there was a 4.8% increase in mortality (IRR 1.048, $p = 0.000$, 95% CI 1.023–1.073); with a 9.4% increase in mortality associated with each 1 °C increase over a minimum temperature of 24 °C (IRR 1.094, $p = 0.000$, 95% CI 1.052–1.138).

Using the dose–response relationship of a 0.9% increase in daily deaths for each degree C over threshold, and the averaged temperature distribution across warm seasons, we estimated an average 21.6 annual heat-attributable deaths during the period 1994/95 to 2005/06. Average maximum temperatures of 2 °C higher, which are projected as a consequence of climate change, would have been associated with 40.2 annual heat-attributable deaths during this period. Alternatively, using the dose–response and distribution of days over the 40 °C cut-off, this estimate was 6 annual heat-attributable deaths, with an estimate of 20.3 deaths if average maximum temperatures had been 2 °C higher during this period.

In relation to morbidity outcomes, shown in Table 1, daily ED presentations showed a 4.4% increase (IRR 1.044, 95% CI 1.033–1.054) with a 10 °C increase in maximum temperature, and also increased in relation to minimum temperature. Renal ED presentations increased by 10.2% (IRR 1.102, 95% CI 1.071–1.135) and 10.7% with 10 °C increases in maximum and minimum temperature, respectively. A 5.1% increase (IRR 1.051, 95% CI 1.028–1.074) in mental health ED presentations was associated with a 10 °C increase in minimum temperature. Significant increases in mental health, cardiovascular and respiratory ED presentations were associated with maximum temperature in unadjusted models; however these effects were not significant when adjusted for air pollutants. Daily hospital admissions showed a 4.1% decrease (IRR 0.959, 95% CI 0.938–0.979) in association with a 10 °C increase in maximum temperature, but no association with minimum temperature.

3.3. Mortality and morbidity in relation to heatwave days

The effect of heatwave days on health outcomes are shown in Table 2, with and without adjustment for air pollutants. An 8.9% increase in daily mortality (IRR 1.089, 95%CI 1.023–1.160) was associated with heatwave compared to non-heatwave days during warm seasons. A 3.4% increase in daily ED presentations (IRR 1.034, 95%CI 1.011–1.057), and a 10.9% increase in renal related presentations (IRR 1.109, 95%CI 1.043–1.180) were also associated with heatwave days, while hospital admissions were decreased by approximately 10% (IRR 0.905, 95%CI 0.854–0.958).

4. Discussion

As a consequence of climate change, the city of Perth is projected to experience an increase in the frequency, intensity and duration of extreme heat. The year 2010 was one of the hottest on record for most of the Perth metropolitan area, with annual mean maximum temperatures 1 °C to 1.5 °C above normal (Australian Bureau of Meteorology, 2011b). Perth also experienced record numbers of days when the maximum temperature was 30 °C or higher in summers 2009/10 and 2010/11 (Australian Bureau of Meteorology, 2011b). The results presented here suggest that a continued increase in summer temperatures could have serious public health implications for the population of Perth. Although a high threshold for heat was apparent, there was a significant increase in mortality associated with temperature above this threshold, particularly at extreme temperatures. There was also a significant increase in morbidity associated with maximum temperature, particularly in relation to renal health.

In comparison to other studies, our maximum temperature threshold estimate of 34–36 °C for mortality in Perth is high. Guest et al.

Table 1
Effect estimates (IRRs) for daily mortality, ED presentations (EDs), and hospital admissions in relation to daily maximum and minimum temperatures (per 10 °C increase), with and without adjustment for O_3, NO_2 and $PM_{2.5}$. Temperatures over thresholds ($T_{max}-T_{threshold}$; $T_{min}-T_{threshold}$) were used as the temperature variables for mortality. Maximum (T_{max}) and minimum (T_{min}) temperatures were used for all other outcomes.

Health outcome	Temperature variable	Unadjusted			Adjusted		
		IRR	p	95% CI	IRR	p	95% CI
Mortality	$T_{max}-T_{threshold}$	1.098	0.012	1.021–1.181	1.098	0.033	1.007–1.196
	$T_{min}-T_{threshold}$	1.282	0.001	1.104–1.489	1.279	0.002	1.093–1.497
Total EDs	T_{max}	1.044	0.000	1.034–1.055	1.044	0.000	1.033–1.054
	T_{min}	1.025	0.009	1.006–1.045	1.023	0.030	1.002–1.043
Mental Health EDs	T_{max}	1.043	0.000	1.021–1.066	1.027	0.185	0.987–1.068
	T_{min}	1.065	0.000	1.042–1.088	1.051	0.000	1.028–1.074
Renal EDs	T_{max}	1.084	0.000	1.056–1.113	1.102	0.000	1.071–1.135
	T_{min}	1.125	0.000	1.092–1.159	1.107	0.000	1.076–1.140
Cardiovascular EDs	T_{max}	1.026	0.008	1.007–1.045	1.022	0.168	0.991–1.054
	T_{min}	1.019	0.072	0.998–1.040	1.014	0.252	0.990–1.039
Respiratory EDs	T_{max}	1.048	0.000	1.022–1.076	1.015	0.382	0.981–1.050
	T_{min}	1.039	0.025	1.005–1.075	1.027	0.115	0.994–1.062
Hospital admissions	T_{max}	0.979	0.001	0.966–0.991	0.959	0.000	0.938–0.979
	T_{min}	0.990	0.364	0.970–1.011	0.996	0.737	0.975–1.018

(1999) reported no obvious heat threshold for Perth, however their study used an earlier period of data (1979–1990). Bambrick et al. (2008) reported a heat threshold of 29 °C for the Perth population aged ≥45 years. Differences in estimates may arise due to the different age groups examined, the periods and sources of mortality data, and methodologies employed. An advantage of the observed/expected approach used here to estimate thresholds is that it makes fewer assumptions about the mortality–temperature relationship than modelling approaches. However, because the baseline is based on a 31-day moving average, and includes hot days in the average values, estimates for excess deaths can be conservative. This is particularly likely if the 31-day window includes a heatwave.

The temperature threshold estimate for Perth is also higher than thresholds reported for other Australian cities, including Brisbane (Tong et al., 2010b), Sydney (Vaneckova et al., 2008a), and Adelaide (Williams et al., 2011). This is not an unexpected result because Perth generally experiences a warmer climate, although summer temperatures are comparable in Adelaide. For much of the metropolitan area of Perth the ‘Fremantle Doctor’ sea breeze provides relief from the heat during the late afternoons, which could partly explain the apparent tolerance to higher temperatures in this population.

Using our estimates for threshold and dose–response relationship, we estimated an average 21.6 annual heat-attributable deaths in Perth during the period 1994 to 2006. If average maximum temperatures had been 2 °C higher during this period, this number would have been almost doubled to 40.2 deaths. A 2 °C increase in average maximum temperature is within the range projected for Perth for 2070 (CSIRO, 2007), and is a widely accepted and quoted goal for global climate change mitigation policies (Steffan, 2011). Our estimate for annual heat-attributable deaths in Perth is substantially lower than that reported by McMichael et al. (2003). The discrepancy can be explained largely by the fact that we have used threshold and dose–response estimates based on Perth data, while the earlier study applied estimates based on a city with a cooler climate (Christchurch, New Zealand).

The impact of extreme heat on renal ED presentations in Perth is consistent with reports of increased renal morbidity during heatwaves in Adelaide (Hansen et al., 2008b), Melbourne (Pincus et al., 2010), and Sydney (Khalaj et al., 2010), and in Northern Hemisphere cities (Josseran et al., 2009; Kovats et al., 2004; Semenza et al., 1999). Renal health can be compromised during extreme heat due to dehydration and hyperthermia leading to electrolyte and water imbalance, and placing stress on the kidneys (Hansen et al., 2008b). ED presentations related to mental health were also sensitive to high minimum temperatures in Perth. Previous psychiatric disorder is a known risk factor for mortality during hot weather (Stafoggia et al., 2006), and an increase in mental health morbidity in relation to heatwaves has been reported for Adelaide (Hansen et al., 2008a; Nitschke et al., 2011) and Sydney (Khalaj et al., 2010). Those with mental health disorders are considered to be particularly vulnerable to extreme heat due to physiological, behavioural and social factors, or the use of specific medications which interfere with the thermoregulation process (Nordon et al., 2009). The possibility of interactive effects should also be considered; with decreased renal function potentially affecting excretion of psychoactive medications.

For mental health, cardiovascular and respiratory ED presentations, the effect of maximum temperature was significant in unadjusted models only, suggesting that air pollutants may contribute to these

Table 2
Effect estimates (IRRs) for daily mortality, ED presentations (EDs) and hospital admissions in relation to heatwave days in Perth (≥35 °C for 3 or more days; at Perth Metro station), with and without adjustment for O_3, NO_2 and $PM_{2.5}$. The number of heatwave days out of the total analysed were: 107/2265 days (mortality); 139/2659 days (ED presentations) and 139/2598 days (hospital admissions).

Health outcome	Unadjusted			Adjusted		
	IRR	p	95% CI	IRR	p	95% CI
Mortality	1.092	0.005	1.026–1.162	1.089	0.008	1.023–1.160
Total EDs	1.043	0.000	1.026–1.060	1.034	0.004	1.011–1.057
Mental health EDs	1.050	0.038	1.003–1.100	1.030	0.152	0.989–1.071
Renal EDs	1.123	0.000	1.083–1.165	1.109	0.001	1.043–1.180
Cardiovascular EDs	1.027	0.420	0.963–1.094	1.017	0.604	0.953–1.086
Respiratory EDs	1.035	0.322	0.967–1.107	1.008	0.830	0.934–1.088
Hospital admissions	0.908	0.000	0.861–0.958	0.905	0.001	0.854–0.958

outcomes during hot weather in Perth. Air pollution is known to be associated with respiratory and cardiovascular disease (Ostro, 2004), however the possible contribution of air pollution to adverse mental health outcomes requires further examination to confirm whether it reflects a true association or a spurious finding. Air pollutants have been found to contribute to the temperature–mortality relationship in several Australian cities. It has been reported that O_3 contributed to excess deaths during the 2004 heatwave in Brisbane, although this effect was minor relative to the effect of heat (Tong et al., 2010a). Similarly, O_3 and PM_{10} accounted for some deaths during summer months in Sydney, but the effect of temperature was higher than that of air pollutants (Vaneckova et al., 2008a). Our Adelaide studies also suggest that O_3 and PM_{10} contribute to the impact of heat on mortality (Williams et al., 2011). The finding that the temperature–mortality relationship in Perth is not confounded by air pollutants suggests that the interactions between weather, air pollution and health are highly location dependent. Significant differences between Australian cities in terms of air pollutants and health outcomes have been reported (Simpson et al., 2005), and these findings reinforce the need for local evidence to quantify the impact of these environmental risk factors on population health.

The health impact of heatwaves in Perth has not previously been investigated. Our results indicate that heatwave days were associated with increased mortality, total and renal ED presentations in Perth. The 8.9% increase in mortality associated with heatwave days represents a considerable impact, and suggests that at least a proportion of the population is vulnerable to heatwave conditions. The availability of disease and age-specific mortality data would enable closer examination of who is most vulnerable to extreme heat. By comparison, the overall effect of heatwaves on mortality in Adelaide, South Australia, is less severe, despite similarities in summer conditions in these cities (Nitschke et al., 2007). This suggests some important differences exist between these populations, possibly related to specific characteristics of summer heat exposure and levels of acclimatisation. Other differences, including sociological, occupational or recreational behaviour may influence health outcomes during extreme heat. It is unlikely that the difference is related to levels of air conditioning as these are comparable between the two cities (Australian Bureau of Statistics, 2009; Western Power, 2007).

In contrast to mortality and ED presentations, our results indicate that hospital admissions decrease during heatwaves in Perth. It is recognised that heat-related deaths can occur rapidly, before hospital care can be provided, and this may explain the apparent discrepancy between increased mortality and decreased hospital admissions (Kovats and Hajat, 2008). The observed increase in ED presentations, without a corresponding increase in admissions, may indicate that these presentations represent patients who die in the ED, or who are treated and discharged without admission. The results for hospital admissions need cautious interpretation because the data included scheduled admissions. While analysis of emergency admissions may better reflect the acute effects of heat, these data were not available for Perth at the time of our request.

The health impacts of extreme heat in Perth have received limited research attention, and this study provides important evidence to inform extreme heat planning for this population. The study has several strengths, including the analysis of different health outcomes and temperature predictors and adjustment for the effects of air pollutants. However, there are a number of limitations, including the problem of misclassification of exposure inherent in ecological studies. Low frequency daily health outcome data for Perth were not readily available, for reasons of confidentiality, so our analysis was limited to the most common outcomes and for all ages. This constraint will need to be overcome to examine other specific disease outcomes and age groups. Further studies could also consider any lag or harvesting effects of heat, and more closely examine the complex relationships between temperature, air pollutants and health for this population.

5. Conclusions

In summary, our results indicate a significant increase in mortality and renal morbidity associated with extreme heat in the population of Perth, Australia. The adverse health effects of hot weather are largely preventable, and public health interventions will be necessary to meet the challenges of more frequent and extreme hot weather projected for this population. Further examination of adverse health outcomes, the identification of vulnerable groups and strategies to protect them from extreme heat could have immediate and future health benefits for this urban population.

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