Science of the Total Environment xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Heat and health in Adelaide, South Australia: Assessment of heat thresholds and temperature relationships

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ARTICLE INFO

Article history:
Received 17 August 2011
Received in revised form 9 November 2011
Accepted 14 November 2011
Available online xxxx

Keywords:
Temperature
Mortality
Morbidity
Air pollution
Extreme heat
Public health

ABSTRACT

Background: Climate change projections have highlighted the need for public health planning for extreme heat. In Adelaide, South Australia, hot weather is characteristic of summer and heatwaves can have a significant health burden. This study examines the heat thresholds and temperature relationships for mortality and morbidity outcomes in Adelaide.

Methods: Daily maximum and minimum temperatures, daily mortality, ambulance call-outs, emergency department (ED) presentations and hospital admissions were obtained for Adelaide, between 1993 and 2009. Heat thresholds for health outcomes were estimated using an observed/expected analysis. Generalized estimating equations were used to estimate the percentage increase in mortality and morbidity outcomes above the threshold temperatures, with adjustment for the effects of ozone (O_3) and particulate matter < 10 μm in mass median aerodynamic diameter (PM_{10}). Effect estimates are reported as incidence rate ratios (IRRs).

Results: Heat-related mortality and morbidity become apparent above maximum and minimum temperature thresholds of 30 °C and 16 °C for mortality; 26 °C and 18 °C for ambulance call-outs; and 34 °C and 22 °C for heat-related ED presentations. Most health outcomes showed a positive relationship with daily temperatures over thresholds. When adjusted for air pollutants, a 10 °C increase in maximum temperature was associated with a 4.9% increase in daily ambulance call-outs (IRR 1.049; 95% CI 1.027–1.072), and a 3.4% increase in mental health related hospital admissions (IRR 1.034; 95% CI 1.009–1.059) for the all-age population. Heat-related ED presentations increased over 6-fold per 10 °C increase in maximum temperature. Daily temperatures were also associated with all-cause and mental health related ED presentations. Associations between temperature over thresholds and daily mortality and renal hospital admissions were not significant when adjusted for ozone and PM_{10}; however at extreme temperatures mortality increased significantly with increasing heat duration.

Conclusions: Heat-attributable mortality and morbidity are associated with elevated summer temperatures in Adelaide, particularly ambulance call-outs, mental health and heat-related illness.

1. Introduction

Climate change is predicted to increase the frequency and duration of heat events across Australia, with a strong increase in the frequency of warm nights (CSIRO, Bureau of Meteorology, Australian Government, 2007). Studies of major Australian cities have reported increased mortality or morbidity from mental and behavioural, renal, cardiovascular, respiratory and cerebrovascular disease, in relation to high ambient temperatures or heatwaves (Bi et al., 2011; Khalaj et al., 2010; Loughnan et al., 2010; Nicholls et al., 2008; Tong et al., 2010a,b; Vaneckova et al., 2008a,b). Whether air pollution has a modifying influence on temperature–health relationships is less

Abbreviations: ED, emergency department; GEE, generalized estimating equation; O_3, ozone; PM_{10}, particulate matter < 10 μm in mass median aerodynamic diameter; IRR, incidence rate ratio; ppb, parts per billion.

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doi:10.1016/j.scitotenv.2011.11.038

well characterised, although a number of studies have demonstrated confounding or interactive effects of air pollutants (Hu et al., 2008; Ren et al., 2006; Tong et al., 2010a,b; Vaneckova et al., 2008a).

The relationship between temperature and mortality typically exhibits a U- or J-shaped curve, with a location specific heat threshold above which mortality increases. The identification of heat thresholds can assist in local planning for extreme heat. In Victoria, threshold temperatures for the populations of Melbourne and regional cities have been incorporated into the Victorian heatwave plan (Victorian Government Department of Health, 2009). For the population of Brisbane, Queensland, deaths and emergency hospital admissions begin to rise at a temperature threshold of around 27 °C (Tong et al., 2010b). The estimated health impact of heat depends on whether estimates are adjusted for humidity and air pollutants (Tong et al., 2010b), including ozone (Tong et al., 2010a) and PM_{10} (Ren et al., 2006). Heat thresholds for mortality in Sydney, New South Wales, have been estimated in the range 23–26 °C (Gosling et al., 2007; Guest et al., 1999; Vaneckova et al., 2008a); and confounding or interaction between temperature and air pollutants, including ozone, PM_{10} and SO_2, have been reported to influence the relationship with mortality (Hu et al., 2008; Vaneckova et al., 2008a,b). Other studies have estimated temperature thresholds and temperature-attributable mortality for other major Australian cities (Bambrick et al., 2008; Guest et al., 1999).

The city of Adelaide, population 1.2 million, is located in a temperate region of South Australia. Previous studies have shown significantly increased rates of ambulance call-outs and hospital admissions during heatwaves of three or more consecutive days of ≥35 °C (Nitschke et al., 2007). Increases in hospital admissions were most notable for mental health (13%), renal illness (7%), and ischaemic heart disease in the 65–74 years group (8%) (Hansen et al., 2008a,b; Nitschke et al., 2007). A recent unprecedented heatwave in January–February 2009, including 9 days of temperatures over 35 °C and 6 consecutive days over 40 °C, was associated with increased mortality in the 15–65 years age group (Nitschke et al., 2011). With the risk of extreme heat increasing in Adelaide, the purpose of this study was to estimate heat thresholds for different health outcomes, and to examine the relationships between warm season temperatures and health outcomes when adjusted for air quality.

2. Materials and methods

2.1. Health data

Daily mortality (1 July 1993–31 March 2009), hospital admissions (1 July 1993–31 March 2009) and emergency department (ED) presentations data (1 July 2003–31 March 2009) were acquired from the South Australian Department of Health. Hospital admissions data were available for all public and private hospitals in the Adelaide metropolitan area, and included emergency and elective admissions. Data for ED presentations were from major public hospitals. For mortality, hospital admissions, and ED presentations, the following international classifications of diseases (ICD, revisions 9 and 10) were used: renal (ICD-9, 580–599.9; ICD-10, N00–N399), mental (ICD-9, 290–294.9; ICD-10, F00–F99), total cardiovascular (ICD-9, 390–459.9; ICD-10, I00 -I99), ischaemic (ICD-9, 410–414.9; ICD-10, I20–I25), respiratory (ICD-9, 460–519.9; ICD-10, J00–J99), and a direct heat-related category comprising dehydration, heat and sunstroke and exposure to excessive heat (ICD-9, 276.5, 992, E900; ICD-10, E86, T67, X30). Ambulance call-out data (1 July 1993–31 March 2009) were provided by the South Australian Ambulance Service (SAAS), using SAAS defined categories of cardiac, respiratory and neurological conditions, and excluding patient transfers between hospitals.

2.2. Meteorological and air quality data

Daily maximum and minimum temperature data (°C) were provided by the Australian Bureau of Meteorology. Data were measured at the Kent Town station (023090) which is representative of the Adelaide metropolitan area. Air quality data for ozone (O_3, daily maximum 1 h average in ppb) and PM_{10} (daily 24-hour average in μg/m^3) from 1 January 2002–31 March 2009 were provided by the Environmental Protection Agency, South Australia. These data were recorded at a centrally located metropolitan site (Netley).

2.3. Data analysis

Analysis was conducted in StataIC10 and 11 (StataCorp. College Station, TX). Estimation of heat thresholds used an observed/expected analysis (Dessai, 2002), which accounts for time and seasonal trends in the data. A 31-day moving average, including 15 days before and after the index day, was used to provide an estimate of expected daily outcome events. Daily excess events were calculated as the difference between the observed daily values and the expected values. Mortality, ambulance call-outs and ED presentations were suitable outcomes for this approach because the daily distributions were similar across the week. Hospital admissions varied substantially by day of the week, largely because of elective admissions, and so were not analysed by this approach.

To relate excess outcome events to daily temperatures, days were grouped into 2 °C intervals of daily maximum or minimum temperature after rounding to the nearest whole degree, and mean daily excess outcomes were 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 and morbidity 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). Analyses included days within the warmer months, 1 October through 31 March, from the period 1 October 1993 to 31 March 2009 (mortality and ambulance call-outs) or 1 October 2003 to 31 March 2009 (ED presentations).

Generalized estimating equations (GEEs) (Diggle et al., 1994) were used to examine the associations between daily temperatures over thresholds and mortality and morbidity outcomes, including ambulance call-outs, ED presentations and specific-cause hospital admissions (renal, mental, cardiovascular and respiratory). Only the warmer months, 1 October through 31 March were considered in these analyses. A negative binomial distribution was assumed for mortality and morbidity outcomes. 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 (from 1 July to 30 June), O_3, and PM_{10}. Linear terms for elevated (over threshold) and extreme temperatures were included, to allow for non-linear relationships. If the change in slope associated with extreme temperatures was not statistically significant, results were reported for elevated temperatures only. The temperature terms were: (i) elevated temperature (maximum or minimum minus threshold temperature, set as 0 if $T<$threshold) and (ii) extreme temperature (maximum minus 40 °C, set as 0 if $T<40$ °C; or minimum minus 26 °C, set as 0 if $T<26$ °C). The pairwise Pearson correlation coefficients for the different maximum temperature terms ranged from 0.36 to 0.52, and for minimum temperature terms from 0.48 to 0.56, thus multicollinearity was not a major concern. Since temperature thresholds were not estimated for hospital admissions, to model this outcome we used the threshold estimates for ED presentations. The incidence rate ratios (IRRs) and 95% confidence intervals (CI) are reported for 1 °C or 10 °C increases in temperature, as indicated.

To examine the effects of heat duration we used a variable coded as 1 through n for consecutive days above a hot day temperature cut-point, and 0 for all days below the cut-point. Hot days were defined by maximum temperature >90th, >95th, or >99th percentile for warm seasons over the period 1994–2009. In this case the reported IRRs are for hot days compared to all other days during the warm season.

When adjusting for air pollutants the periods of data analysed were: 1 January 2002 to 31 March 2009 for mortality, ambulance call-outs, and hospital admissions; and 1 October 2003–31 March 2009 for ED presentations; with unadjusted analyses for the corresponding periods for comparison. Days with missing data for maximum temperature (2 days), minimum temperature (2 days), and O_3 (3 days) were omitted from the analysis. The level of missing data for PM_{10} (5.5%) meant that interpolation was necessary to generate a complete dataset. Linear interpolation was used to impute missing PM_{10} values which is appropriate for short gaps (Junninen et al., 2004).

3. Results

3.1. Investigation of temperature thresholds for health outcomes

As a preliminary investigation mean daily mortality, ambulance call-outs and ED presentations were plotted in relation to daily maximum and minimum temperatures. For mortality and ambulance call-

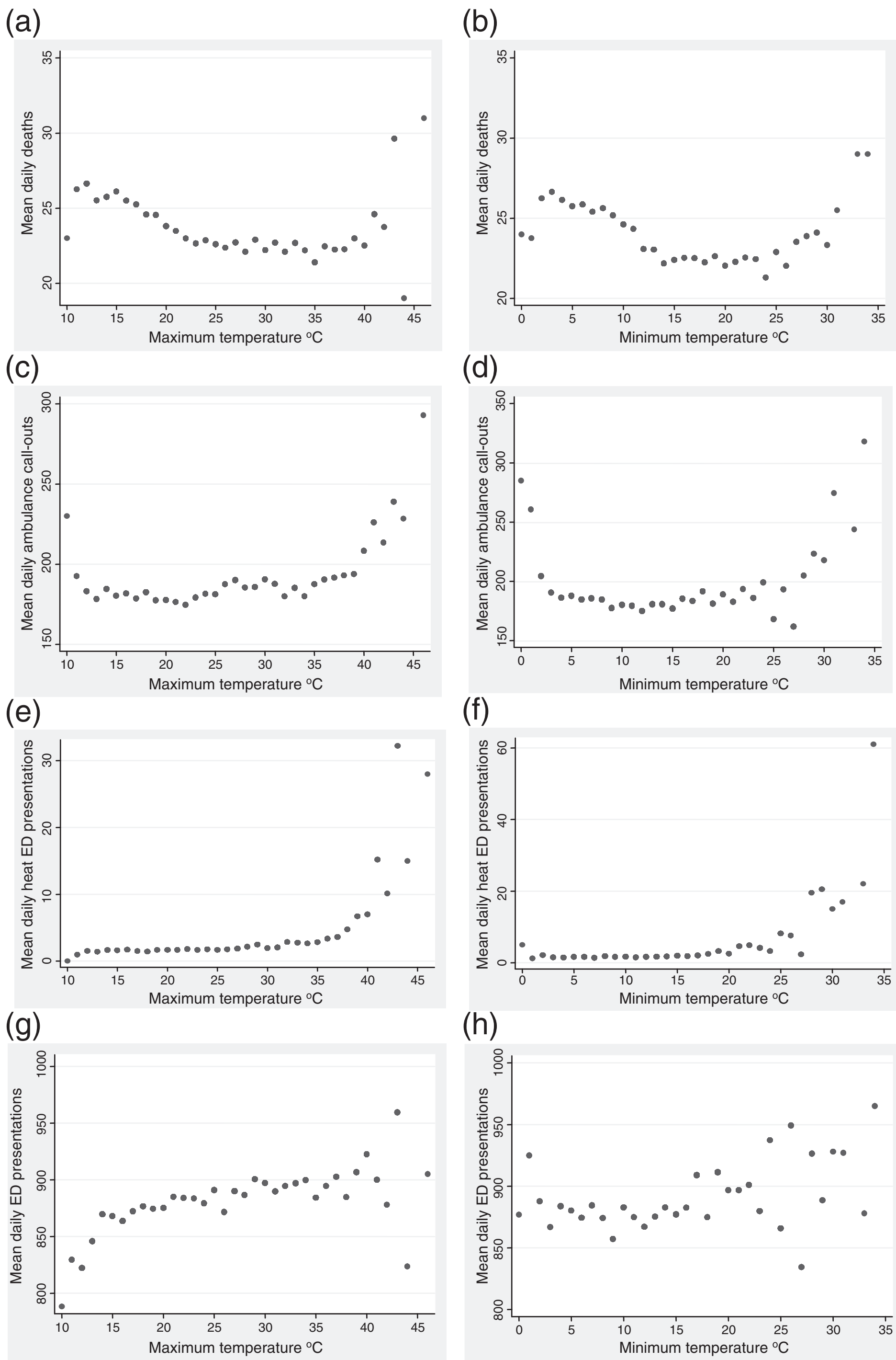

Fig. 1. Mean daily deaths, ambulance call-outs, heat-related ED presentations and total ED presentations in relation to daily maximum and minimum temperatures, Adelaide. Plots show mean daily deaths (a, b); ambulance call-outs (c, d); heat-related ED presentations (e, f); and all-cause ED presentations (g, h), in relation to rounded daily maximum and minimum temperatures. Data were from the period 1 July 1993–31 March 2009 (deaths, ambulance call-outs) and 1 July 2003–31 March 2009 (ED presentations).

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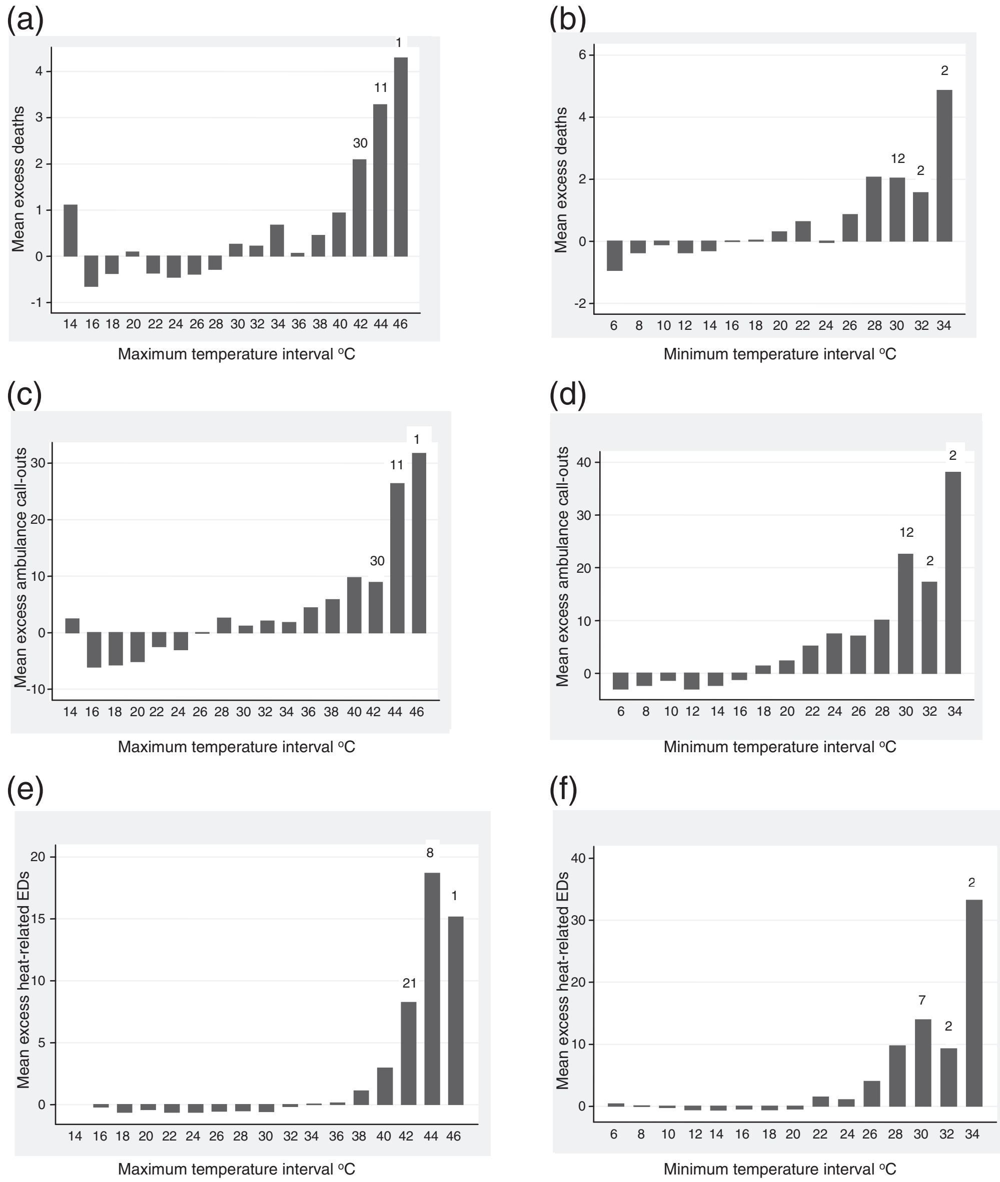

Fig. 2. Mean excess daily deaths, ambulance call-outs and heat-related ED presentations in relation to daily temperatures, Adelaide. Plots show excess daily deaths (a, b); ambulance call-outs (c, d); and heat-related ED presentations (e, f), in relation to 2 °C intervals of maximum and minimum temperature on days within Adelaide warm seasons, 1 October through 31 March. Data were from 1 October 1993–31 March 2009 (mortality and ambulance call-outs) and 1 October 2003–31 March 2009 (ED presentations). For the highest temperature intervals, the number of days represented is indicated above the columns.

outs a J-shaped relationship with temperature was evident (Fig. 1(a–d)). Plots of mortality due to respiratory, cardiovascular or ischaemic heart disease were similar to all-cause mortality (not shown). Mean daily ED presentations, particularly heat-related, increased with increasing temperature (Fig. 1(e–h)). An increase was also apparent for mental and renal-related ED presentations, but no positive relationship was observed for respiratory, cardiovascular or ischaemic heart disease ED presentations (not shown).

An observed/expected descriptive analysis was undertaken to estimate heat thresholds for different outcomes. Fig. 2 shows plots of mean daily excess mortality, ambulance call-outs, and heat-related ED presentations against 2 °C intervals of daily maximum or minimum temperature. These plots indicate that heat-related mortality and morbidity become apparent above maximum and minimum temperature thresholds of 30 °C and 16 °C for mortality, 26 °C and 18 °C for ambulance call-outs, and 34 °C and 22 °C for heat-related ED presentations. Table 1 shows the heat threshold estimates for specific health outcomes, for the all-age and ≥65-years age groups.

3.2. Relationships between daily temperatures and health outcomes

The relationships between health outcomes and temperatures over thresholds were examined using linear terms for (i) elevated (over threshold) and (ii) extreme temperatures, because of the observed non-linearity in Figs. 1 and 2. The cut-points for extreme temperatures were set at 40 °C (maximum) and 26 °C (minimum), as suggested from Figs. 1 and 2. The results are summarised in Table 2, and represent analysis of the full period of available data for each health outcome. For most outcomes there was a positive association with elevated temperatures (over threshold) but the change in slope at extreme temperatures was not statistically significant. For heat-related ED presentations however there was a further increase

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of 13.8% per 1 °C for extreme maximum temperatures. For all-cause and mental health related ED presentations there was a significant decrease in effect at extreme temperatures. Overall the results were comparable for the ≥65-years age group (not shown).

Tables 3 and 4 summarise the results when adjusted for O_3 and PM_{10} levels. For the outcomes in Table 3 the elevated temperature variable was used and, because of the small effect sizes, results are shown for a 10 °C increase in temperature. For the all-age population, a 10 °C increase in temperature over threshold was associated with an increase of 4.9% in daily ambulance call-outs (IRR 1.049, 95% CI 1.027–1.072) in relation to maximum temperature, and a 9.3% increase (IRR 1.093, 95% CI 1.043–1.145) in relation to minimum temperature, when adjusted for ozone and PM_{10} (Table 3). Similar effects were apparent for ambulance call-outs for the population ≥65-years. Daily ED presentations showed significant increases in relation to maximum and minimum temperatures in the population ≥65-years (Table 3). For mental health outcomes, ED presentations increased in relation to minimum temperature for the all-age and ≥65-years groups, and hospital admissions (all-age) increased in relation to maximum temperature (Table 3). The associations between daily temperatures and mortality or renal hospital admissions were not significant when adjusted for air pollutants.

For the outcomes shown in Table 4 both the elevated and extreme temperature variables were used, and results are shown for a 1 °C increase in temperature. When adjusted for O_3 and PM_{10} there were substantial increases in daily heat-related ED presentations per 1 °C increase in maximum temperature over threshold (32 °C), with a further increase in the extreme temperature range. All cause EDs increased with elevated minimum temperatures, but this effect decreased in the extreme temperature range (Table 4).

The effect of increasing heat duration on mortality and ambulance call-outs is shown in Table 5. Daily mortality increased by 1.0% (IRR 1.010; 95% CI 1.004–1.016) or 7.0% (IRR 1.070; 95% CI 1.031–1.111), with each successive day over the 95th and 99th percentiles for maximum temperature, respectively. Daily ambulance call-outs increased by 1.1% (IRR 1.011; 95% CI 1.009–1.013) up to 4.6% (IRR 1.046; 95% CI 1.021–1.071) with each successive day over the 95th and 99th percentiles for daily maximum temperature, respectively.

4. Discussion

For the population of Adelaide, South Australia, heatwaves have been associated with increased ambulance call-outs and hospital admissions, particularly for mental and renal illness (Hansen et al., 2008a,b; Nitschke et al., 2007). However, the heat thresholds and temperature-relationships had not been explored for different health outcomes, and possible confounding by air pollution had not been examined.

Table 1
Estimated heat thresholds for health outcomes in Adelaide. Maximum and minimum temperature thresholds were estimated for the all-age and ≥65-years (65+) populations.

Outcome	Age group	Estimated heat threshold (°C)	
		Maximum	Minimum
Mortality	All age	30	16
	65+	30	16
Ambulance call-outs	All age	26	18
	65+	26	18
EDs	All age	26	16
	65+	28	18
EDs heat-related	All age	34	22
	65+	32	22
EDs mental health	All age	32	16
EDs renal health	All age	34	18
	65+	34	18

Table 2
Effect estimates (IRRs) for daily mortality, ambulance call-outs, ED presentations, and hospital admissions in relation to daily maximum and minimum temperatures. The IRRs were estimated in relation to linear terms for elevated temperatures (over thresholds) and extreme temperatures (≥40 °C Tmax; ≥26 °C Tmin). Results are for the all-age population and represent data from 16 warm seasons for mortality, ambulance call-outs and hospital admissions, and 6 seasons for ED presentations.

Health outcome	Temp	Elevated temperature per 1 °C (over threshold)			Extreme temperature per 1 °C (over 40° max; over 26° min)		
	Max/Min	IRR	p	95% CI	IRR	p	95% CI
Mortality	Max	1.006	0.003	1.002–1.010	1.019	0.269	0.985–1.054
	Min	1.005	0.001	1.002–1.008	1.011	0.356	0.987–1.036
Ambulance call-outs	Max	1.005	0.000	1.004–1.006	1.010	0.263	0.993–1.028
	Min	1.010	0.000	1.007–1.012	1.001	0.869	0.986–1.017
EDs	Max	1.001	0.011	1.000–1.002	0.985	0.036	0.970–1.000
	Min	1.004	0.000	1.003–1.005	0.991	0.007	0.984–0.997
EDs heat-related	Max	1.171	0.000	1.122–1.222	1.138	0.003	1.046–1.238
	Min	1.175	0.000	1.113–1.240	1.006	0.804	0.959–1.056
EDs mental	Max	1.011	0.000	1.006–1.016	0.987	0.027	0.976–0.999
	Min	1.012	0.001	1.005–1.019	0.998	0.655	0.988–1.007
EDs renal	Max	1.008	0.201	0.996–1.021	1.007	0.800	0.953–1.065
	Min	1.009	0.185	0.996–1.023	1.019	0.471	0.968–1.073
All cause admissions	Max	1.002	0.052	1.000–1.003	0.997	0.844	0.969–1.026
	Min	1.002	0.039	1.000–1.005	1.000	0.978	0.988–1.011
Renal admissions	Max	1.006	0.000	1.003–1.010	0.970	0.287	0.916–1.026
	Min	1.010	0.000	1.005–1.015	1.013	0.408	0.982–1.045
Mental-health admissions	Max	1.003	0.007	1.001–1.005	1.018	0.281	0.985–1.052
	Min	1.004	0.004	1.001–1.007	1.024	0.050	1.000–1.049
Cardiovascular admissions	Max	1.000	0.981	0.998–1.002	0.992	0.631	0.958–1.026
	Min	1.001	0.653	0.998–1.003	1.000	0.995	0.981–1.020
Respiratory admissions	Max	1.003	0.023	1.000–1.005	1.010	0.705	0.959–1.063
	Min	1.003	0.049	1.000–1.007	0.999	0.922	0.977–1.022

We have estimated maximum temperature thresholds of approximately 26 °C for ambulance call-outs and ED presentations, and 30 °C for mortality, which are mild temperatures for warm seasons in Adelaide. There were positive associations between elevated temperatures (over thresholds) and mortality, ambulance call-outs, ED presentations and hospital admissions. Graphical representations of the data suggested a further rise in mortality and morbidity at extreme temperatures. However for most outcomes there was no significant change in slope associated with extreme temperatures, possibly reflecting the limited data at extremes.

Our estimates for heat thresholds were comparable for the all-age and the ≥65-years age groups, even though it is widely reported that the elderly are more vulnerable to heat (Basu and Samet, 2002). It is possible that this result arises because the majority of events, particularly for mortality, occur in the population ≥65-years. Alternatively our approach may have lacked the sensitivity to detect small differences in thresholds. It is also possible that heat thresholds are similar, with the older population being more sensitive to heat beyond these thresholds. However, with the exception of some specific ED presentations, our results are not entirely consistent with this possibility.

The mortality heat threshold of 30 °C agrees with that estimated by Bambrick et al. (2008) using a modelling approach and maximising log-likelihood over a 1 °C grid. Guest et al. (1999) used an observed-expected mortality analysis and reported no obvious heat threshold for Adelaide, however this was using an earlier period of data (1979–1990). The 30 °C threshold is higher than estimates for other Australian cities, Brisbane (Tong et al., 2010b) and Sydney (Vaneckova et al., 2008a), which is not unexpected because the Adelaide population is acclimatised to a hotter climate.

We did not find evidence of heat thresholds for all the health outcomes examined in this study. In some cases this was due to the limited numbers of daily excess events, while other outcomes did not show a positive relationship with temperature. The thresholds estimated reflect the lower levels of heat sensitivity of the population, and triggers for public health interventions would be expected to be

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Table 3
Effect estimates (IRRs) for daily mortality, ambulance call-outs, ED presentations and hospital admissions in relation to daily temperatures, adjusted for ozone and PM_{10}. The IRRs were estimated in relation to 10 °C increases in daily maximum and minimum temperatures over thresholds (thresh °C), with and without adjustment for ozone and PM_{10}. Results for the all-age and ≥65-years (65+) age groups are shown, for the period Jan 2002 to March 2009; or Oct 2003 to March 2009 for ED presentations.

Health outcome	Age group	Temp (thresh °C)	Unadjusted			Adjusted O_3, PM_{10}		
			IRR	p	95% CI	IRR	p	95% CI
Mortality	All age	Max (30)	1.045	0.069	0.996–1.097	1.028	0.567	0.934–1.132
	65+	Max (30)	1.037	0.034	1.003–1.071	1.027	0.548	0.941–1.123
	All age	Min (16)	1.054	0.020	1.008–1.102	1.042	0.259	0.970–1.119
	65+	Min (16)	1.044	0.004	1.014–1.074	1.037	0.200	0.981–1.095
Ambulance call-outs	All age	Max (26)	1.060	0.000	1.046–1.074	1.049	0.000	1.027–1.072
	65+	Max (26)	1.061	0.000	1.044–1.079	1.065	0.000	1.041–1.090
	All age	Min (18)	1.117	0.000	1.077–1.158	1.093	0.000	1.043–1.145
	65+	Min (18)	1.116	0.001	1.048–1.187	1.103	0.014	1.020–1.193
EDs	65+	Max (26)	1.039	0.000	1.028–1.051	1.036	0.004	1.011–1.062
	65+	Min (18)	1.071	0.000	1.038–1.106	1.058	0.016	1.011–1.108
EDs heat-related	All age	Min (22)	6.486	0.000	3.033–13.87	6.511	0.000	2.785–15.22
	65+	Min (22)	11.26	0.000	4.489–28.24	9.101	0.000	3.201–25.88
EDs renal	All age	Max (34)	1.105	0.314	0.910–1.342	1.076	0.482	0.877–1.321
	65+	Max (34)	1.298	0.069	0.979–1.719	1.222	0.145	0.933–1.600
	All age	Min (18)	1.127	0.093	0.980–1.300	1.120	0.088	0.983–1.277
	65+	Min (18)	1.235	0.060	0.991–1.540	1.190	0.087	0.975–1.453
EDs mental health	65+	Max (32)	1.293	0.007	1.074–1.556	1.154	0.108	0.970–1.373
	All age	Min (16)	1.122	0.002	1.043–1.207	1.079	0.002	1.027–1.133
	65+	Min (16)	1.242	0.001	1.090–1.416	1.143	0.026	1.016–1.285
All cause admissions	All age	Max (26)	1.015	0.095	0.997–1.034	0.988	0.370	0.962–1.015
	All age	Min (16)	1.030	0.244	0.980–1.082	1.009	0.782	0.949–1.073
Renal admissions	All age	Max (26)	1.066	0.000	1.032–1.101	1.024	0.312	0.978–1.071
	All age	Min (16)	1.108	0.019	1.017–1.208	1.064	0.172	0.973–1.163
Mental health admissions	All age	Max (26)	1.027	0.001	1.011–1.044	1.034	0.007	1.009–1.059
	All age	Min (16)	1.038	0.001	1.015–1.061	1.024	0.238	0.984–1.065
Cardiovascular admissions	All age	Max (26)	0.990	0.292	0.972–1.008	0.974	0.097	0.945–1.005
	All age	Min (16)	1.032	0.154	0.988–1.078	1.035	0.240	0.977–1.096
Respiratory admissions	All age	Max (26)	1.025	0.160	0.990–1.061	0.996	0.880	0.944–1.051
	All age	Min (16)	1.026	0.267	0.980–1.075	1.004	0.858	0.957–1.054

set at higher temperatures. The current extreme heat warning for Adelaide is triggered by forecast average daily temperatures of ≥32 °C for three or more consecutive days (South Australian State Emergency Service, 2009). In a separate study we have found that events reaching this level are associated with significant increases in mortality and morbidity (Williams et al., 2011).

In relation to disease specific outcomes, both renal and mental health outcomes were associated with elevated temperatures, consistent with results for heatwave days in Adelaide (Hansen et al., 2008a, b; Nitschke et al., 2007, 2011). The increase in mental health related outcomes reflects the heightened vulnerability to heat among those with mental disorders; which is attributed to behavioural and social factors, or the use of medications which interfere with the thermoregulatory process (Hansen et al., 2008a; Nordon et al., 2009). The risks to renal health are attributed to dehydration and electrolyte and water imbalance causing stress on the kidneys (Hansen et al., 2008b). Renal hospital admissions, but not ED presentations, were significantly associated with daily temperatures in this study. This difference could be explained if coding within emergency departments does not identify all renal-related presentations, leading to possible under-reporting for this outcome. In relation to other disease specific outcomes, our results indicate a weak association between temperature and respiratory hospital admissions, but no effects on cardiovascular admissions were apparent.

When ozone and PM_{10} were included in models the associations between daily temperatures and mortality and renal hospital admissions were no longer significant, suggesting confounding of these relationships. Alternatively, this may be a consequence of the reduced predictive power of the adjusted models, compounded by the shorter period of air quality data available for analysis. Ozone levels increase on extremely hot days due to the effect of sunlight on photochemical smog formation; and studies have consistently reported that high ozone levels contributed to mortality during heatwaves in Europe (Dear et al., 2005; Filleul et al., 2006; Fischer et al., 2004; Stedman, 2003),

Table 4
Effect estimates (IRRs) for daily ED presentations in relation to temperature, adjusted for ozone and PM_{10}. The IRRs were estimated per 1 °C increase in daily maximum and minimum temperatures using linear terms for (i) elevated (elev) temperatures (over thresholds) and (ii) extreme (ext) temperatures. Unadjusted analyses for the equivalent period, Oct 2003 to Mar 2009, are shown for comparison. Results are for the all-age or ≥65-years (65+) age groups.

Health outcome	Age group	Temp (threshold °C)	Temp var	Unadjusted			Adjusted O_3, PM_{10}		
				IRR	p	95% CI	IRR	p	95% CI
EDs	All age	Max (30)	elev	1.001	0.011	1.000–1.002	1.001	0.490	0.999–1.002
			ext	0.985	0.036	0.970–0.999	0.986	0.068	0.972–1.001
	All age	Min (16)	elev	1.004	0.000	1.003–1.005	1.004	0.000	1.002–1.005
			ext	0.991	0.007	0.984–0.997	0.991	0.010	0.984–0.998
EDs heat-related	All age	Max (32)	elev	1.171	0.000	1.122–1.222	1.150	0.000	1.084–1.220
			ext	1.138	0.003	1.046–1.238	1.177	0.003	1.056–1.313
	65+	Max (32)	elev	1.164	0.000	1.105–1.227	1.139	0.001	1.055–1.229
			ext	1.183	0.001	1.068–1.310	1.231	0.002	1.080–1.404
EDs mental health	All age	Max (32)	elev	1.011	0.000	1.006–1.016	1.001	0.792	0.993–1.010
			ext	0.987	0.027	0.976–0.999	1.006	0.680	0.978–1.034

Please cite this article as: Williams S, et al, Heat and health in Adelaide, South Australia: Assessment of heat thresholds and temperature relationships, Sci Total Environ (2011), doi:10.1016/j.scitotenv.2011.11.038

Table 5
Effect estimates (IRRs) for daily mortality and ambulance call-outs in relation to heat duration. The IRRs are for increasing number of days over maximum temperature cut-offs (>90th, >95th and >99th percentiles for warm seasons; equivalent to ≥35 °C; ≥37 °C and ≥41 °C, respectively), with adjustment for O_3 and PM_{10}. The total number of days in each hot day category was; >90th (181 days), >95th (111 days), >99th (25 days) out of 1359 days analysed in the period 1 January 2002 to 31 March 2009. Results are for the all-age population.

Outcome	Hot day category	IRR	p-value	95% CI
Mortality	>90th	1.009	0.185	0.996–1.023
	>95th	1.010	0.001	1.004–1.016
	>99th	1.070	0.000	1.031–1.111
Ambulance call-outs	>90th	1.014	0.002	1.005–1.023
	>95th	1.011	0.000	1.009–1.013
	>99th	1.046	0.000	1.021–1.071

and in Australia (Tong et al., 2010a; Vaneckova et al., 2008a). Studies in Australian cities have also identified associations between ozone and respiratory mortality and hospital admissions (Simpson et al., 2005a, b), and urgent emergency department visits for cardiovascular and chest pain syndromes (Turner et al., 2007). In relation to PM_{10} levels, the effect of temperature is less clear, although bushfires during summer can lead to sustained high levels of PM_{10} (Spickett et al., 2011). Associations between PM_{10} and total mortality (Simpson et al., 2005b), childhood respiratory emergencies (Barnett et al., 2005) and cardiovascular emergencies in the elderly (Jalaludin et al., 2006) have been identified in Australian cities. Although PM has not been associated with renal outcomes, it is biologically plausible that the inflammation and oxidative stress linked to PM exposure could underlie a range of common diseases (Brook, 2008).

In terms of heat duration, there was an association between the number of days of extreme heat and increased mortality and ambulance call-outs, most notably when considering days over the 99th percentile of warm season maximum temperatures. This is consistent with previously reported results for morbidity outcomes during heatwaves in Adelaide (Nitschke et al., 2011). The effect of heat duration on mortality could also be related to increased heat intensity, because of the strong correlation with duration.

This study extends our understanding of the relationships between temperature and health outcomes in Adelaide. There are a number of limitations, including the possible misclassification of exposures inherent in ecological studies. The estimation of excess daily mortality and morbidity, using a 31-day moving average baseline, was not applicable to hospital admissions, as has been discussed. Furthermore, it is possible that heatwaves of extended duration may inflate this baseline, leading to an underestimation of excess events for days within or near to heatwaves. Although the availability of air quality data was limited, our analysis across 8 warm seasons indicates that ozone and PM_{10} may contribute to mortality and morbidity during hot weather in Adelaide. Along with more extreme hot weather, an increase in air pollution in urban areas is a likely consequence of global warming (Harlan and Ruddell, 2011; Spickett et al., 2011). Further investigation of the complex associations between temperature, air quality and health will be important in reducing the impacts of these environmental risk factors.

5. Conclusions

The estimation of heat thresholds and temperature relationships for mortality and morbidity outcomes in Adelaide has identified a significant health burden at elevated temperatures for this population. Daily rates of ambulance call-outs and ED presentations, particularly for mental health and heat-related illness, show the strongest associations with daily temperatures when adjusted for ozone and PM_{10}. The results have important implications for ongoing public health planning for extreme heat in Adelaide.

Acknowledgements

We acknowledge the Department of Health, South Australia, and South Australian Ambulance Service for providing health outcome data; the Bureau of Meteorology, South Australia, for temperature data; and the Environment Protection Authority, South Australia, for providing air quality data for this project. This work was supported by the Australian Research Council [grant number DP0880933 to P.B.]

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Please cite this article as: Williams S, et al, Heat and health in Adelaide, South Australia: Assessment of heat thresholds and temperature relationships, Sci Total Environ (2011), doi:10.1016/j.scitotenv.2011.11.038