ORIGINAL ARTICLE

The impact of heatwaves on mortality and emergency hospital admissions from non-external causes in Brisbane, Australia

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Accepted 8 June 2011
Published Online First 30 June 2011

ABSTRACT

Objectives Heatwaves can have significant health consequences resulting in increased mortality and morbidity. However, their impact on people living in tropical/subtropical regions remains largely unknown. This study assessed the impact of heatwaves on mortality and emergency hospital admissions (EHAs) from non-external causes (NEC) in Brisbane, a subtropical city in Australia.

Methods We acquired daily data on weather, air pollution and EHAs for patients aged 15 years and over in Brisbane between January 1996 and December 2005, and on mortality between January 1996 and November 2004. A locally derived definition of heatwave (daily maximum ≥37°C for 2 or more consecutive days) was adopted. Case–crossover analyses were used to assess the impact of heatwaves on cause-specific mortality and EHAs.

Results During heatwaves, there was a statistically significant increase in NEC mortality (OR 1.46; 95% CI 1.21 to 1.77), cardiovascular mortality (OR 1.89; 95% CI 1.44 to 2.48), diabetes mortality in those aged 75+ (OR 9.96; 95% CI 1.02 to 96.85), NEC EHAs (OR 1.15; 95% CI 1.07 to 1.23) and EHAs from renal diseases (OR 1.41; 95% CI 1.09 to 1.83). The elderly were found to be particularly vulnerable to heatwaves (eg, for NEC EHAs, OR 1.24 for 65–74-year-olds and 1.39 for those aged 75+).

Conclusions Significant increases in NEC mortality and EHAs were observed during heatwaves in Brisbane where people are well accustomed to hot summer weather. The most vulnerable were the elderly and people with cardiovascular, renal or diabetic disease.

What this paper adds

- Although heatwaves can have significant health consequences, there is no global definition of heatwaves because local regional variability influences the impact of extreme heat, and it also remains largely unknown whether heatwaves have any impact on people who are well accustomed to warm weather.
- This study investigated the impacts of heatwaves on both cause-specific mortality and emergency hospital admissions from non-external causes using a locally-defined definition in Brisbane during 1996–2005.
- We found that heatwaves had significant effects on mortality and emergency hospital admissions in a subtropical city where residents are well accustomed to hot summers.

INTRODUCTION

As climate change continues, the frequency, intensity and duration of heatwaves are likely to increase.[1] Heatwaves, especially severe ones like the 2003 European heatwave, can have significant health consequences resulting in increased mortality and morbidity, particularly among the elderly, young children, people with chronic illnesses and in socially and economically disadvantaged groups.[2–9] Exposure to thermal stress has a significant impact on human health, and is responsible for a quantifiable burden of mortality and morbidity.[10–19]

It is difficult to create a uniform heatwave definition because regional variability plays a large role in determining heat-related impacts. Recent studies have found that heatwave-related mortality and morbidity depend on the acclimatisation of the population.[1 9–11 20 21] Populations in warmer climates tend to have more access to air conditioning and swimming pools, as well as more experience in dealing with heat. What would be described as a heatwave in a temperate region may be considered a normal day in a subtropical region.

In a previous study we assessed heat-related health outcomes using different heatwave definitions.[10] Based on those results, we defined a heatwave in Brisbane as a daily maximum temperature of at least 37°C for two or more consecutive days. According to this definition, three heatwaves occurred between 1996 and 2005 (20–21 January 2000, 24–26 December 2001 and 21–22 February 2004). This study extended our previous work by investigating the impacts of heatwaves on both cause-specific mortality and emergency hospital admissions (EHAs) from non-external causes (NEC) using daily data collected in Brisbane.

METHODS

Brisbane is the capital city of Queensland. It is located in the south-east corner of the state (27°29'S, 153°8'E) and has a subtropical climate. It is Australia's third largest city (after Sydney and Melbourne), covering an urban area of 1326.8 km^2

with a population of 991 260 on 30 June 2006.[22] At that time, 18% of the population were aged 0–14, 71% were aged 15–64 and 11% were aged 65+. We chose Brisbane as the study site because it has the highest population density in subtropical Australia. Therefore, an assessment of heat-related health effects has significant public health implications in relation to the mitigation and prevention of the impact of heatwaves. The data used in this study were 10-year time series of climate, air pollution and EHA data from 1 January 1996 to 31 December 2005. Mortality data were only obtainable up to November 2004 due to the time lag between deaths and their registration by state authorities.

Climate and air pollution data

Daily climate data from five monitoring stations in Brisbane were obtained from the Australian Bureau of Meteorology. The daily arithmetic average values of maximum temperature and relative humidity were computed using the data collected from these stations. Maximum temperature was the highest temperature measured in 24 h after 09:00 h. Relative humidity is the amount of water in the air relative to the maximum amount of water that the air can hold at a given temperature (expressed as a percentage). Air temperatures and relative humidity were measured every 3 h. We used the maximum temperature in this study, because the highest air temperature often occurred around noon to afternoon, a time during which relatively more people may be outside.

Air pollution data were provided by the Queensland Department of Environment and Resource Management (formerly the Queensland Environmental Protection Agency), and included ambient 24 h average concentrations of particulate matter with diameter less than 10 μm (PM_{10}), daily maximum 1 h average nitrogen dioxide (NO_2) and ozone (O_3). For each day, average air pollution concentrations were averaged across 17 available monitoring stations in Brisbane. Approximately 5% of values were missing. When data were missing for a particular monitoring station on a given day, the observations recorded from the other monitoring stations were used to calculate the daily average values.

Mortality and EHA data

Mortality data were provided by the Office of Economic and Statistical Research of the Queensland Treasury. The data included date of death, sex, age, statistical local area of residence and cause of death. Daily data on EHAs were provided by the Health Information Centre of Queensland Health. The data were admission counts by date, principal diagnosis, age group and the number of admitted patient episodes of care. Stratified analysis by gender was not possible since the release of this information from the EHA datasets was considered a potential breach of confidentiality. Cause-specific mortality and EHAs were categorised according to the International Classification of Diseases (revisions 9 and 10) and defined as cardiovascular (ICD-9, 390-459; ICD-10, I00–I99), diabetes (ICD-9, 250; ICD-10, E10–E14), ischaemic stroke (ICD-9, 433-435; ICD-10, I63, I65–I66), mental health (ICD-9, 290-319; ICD-10, F00–F99), renal (ICD-9, 580-629; ICD-10, N00–N39), respiratory diseases (ICD-9, 460-519; ICD-10, J00–J99) and non-external causes (ICD-9, <800; and all ICD-10 codes excluding S00–U99 for external causes).

Data analysis

Statistical analyses were conducted using daily data on climate, air pollution and health outcomes. Case–crossover analyses were used to assess the relationship between heatwaves and health outcomes. The case–crossover approach is useful because it controls for trends and seasonal patterns in the dependent and independent variables by design.[23 24] We used the time-stratified case–crossover with a stratum length of 28 days, and matched control days to case days using day of the week (this gives 3 control days per case day). Lagged effects (lag 1, lag 2 and lags 0–2) of heat on mortality and EHAs (NEC) were also assessed using the same method. Three heatwaves (7 heatwave days) were identified using the local heatwave definition during the study period. Therefore, data for three 28-day strata (84 days) were used in the case–crossover analysis. The main independent variable was heatwave day (yes/no). The dependent variable was the daily number of deaths or EHAs by age group (15–64, 65–74, 75+ years and all ages). We also adjusted for linear effects of humidity and air pollutants (PM_{10}, NO_2 and O_3). Humidity and air pollutants were included with same-day concentrations. However, when the lagged effects of heat on NEC mortality and EHAs were assessed, lagged concentrations of humidity and air pollution were also used. A conditional logistic regression model was used in the final multivariable analyses. All case–crossover analyses were conducted using SAS statistical software.[25]

RESULTS

Three heatwaves were identified during the study period, which were all short (ie, 2 or 3 days each). Table 1 presents summary statistics of the daily climate, air pollutants and health outcomes for Brisbane for the 7 heatwave days and 21 control days. The average maximum temperature during heatwave days was much higher (by 8.5°C) than for the control days; however, the average relative humidity was lower. The average concentrations of PM_{10}, NO_2 and O_3 during heatwave days were higher than those during control days, but the average levels of these concentrations (PM_{10}, NO_2 and O_3) both on heatwave days and on control days were lower than the National Air Quality Standards in Australia (50 μg/m^3, 120 ppb and 100 ppb, respectively). There were a daily average of 23 deaths and 161 EHAs during heatwave days, compared to 15 deaths and 138 EHAs during control days. Table 2 shows the daily average of cause-specific deaths and EHAs during the three heatwaves (7 case days and 21 control days).

Table 1 Summary of daily climate and air pollutants for NEC deaths and EHAs for Brisbane, 1996–2005

Variable	Mean	SD	Min	25%	Median	75%	Max
Heatwave days							
Tmax (°C)	39.1	1.3	37.9	38	38.7	39.8	41.5
Humidity (%)	60.3	6.5	51.1	51.4	62.9	64.6	67.4
PM_{10} (μg/m^3)	27.2	5.5	20.5	23	26.6	32.4	36.1
NO_2 (ppb)	18.4	4.2	13.7	15.5	17	19.9	26.8
O_3 (ppb)	49.8	8.8	40.8	43	49.2	51.8	67.8
Deaths (162)	23	11	12	14	20	35	42
EHAs (1124)	161	35	113	121	165	196	202
Control days							
Tmax (°C)	30.6	3	26.1	28.8	29.9	32.3	37.2
Humidity (%)	71.2	7.7	53.8	65.3	71.9	76.7	86.3
PM_{10} (μg/m^3)	19.1	6	11	14.2	18.2	22.9	32.9
NO_2 (ppb)	13.8	3.6	8.2	11.1	12.9	17.3	19.7
O_3 (ppb)	33.4	9.8	17	26.8	32	39.6	55.7
Deaths (317)	15	4	10	13	15	17	25
EHAs (2888)	138	14	103	133	140	147	160

EHAs, emergency hospital admissions; NEC, non-external causes; PM_{10}, particulate matter with diameter less than 10 μm; Tmax, maximum temperature.

Table 2 Daily average cause-specific deaths and emergency hospital admissions (EHAs) during heatwaves in Brisbane, 1996–2005

Disease	Deaths		EHAs	
	Case days	Control days	Case days	Control days
Cardiovascular	12.6	6.3	24.3	23.0
Diabetes	0.6	0.2	2.3	1.9
Ischaemic stroke	0.3	0.1	1.0	1.5
Mental health	0.4	0.4	15.3	17.6
Renal	0.6	0.5	12.3	8.2
Respiratory	2.1	1.4	19.9	16.7

Spearman correlations between climate variables and air pollutants show that only the correlation between NO_2 and O_3 was statistically significant during both heatwave days ($r=0.78$, $p<0.05$) and control days ($r=0.58$, $p<0.01$). There were positive correlations (although not statistically significant) between humidity and air pollutants during heatwave days ($r=0.54$ to 0.63) but inverse correlations (including a statistically significant one) during control days ($r= -0.15$ to -0.68). There were moderate to high correlations between maximum temperature and air pollutants on control days ($r=0.59$ to 0.77, $p<0.01$).

Figure 1 shows that maximum temperature was positively associated with daily deaths and EHAs in the three 28-day strata which were used in case–crossover analysis. There was an increase in NEC mortality and EHAs during the first and third heatwave periods compared to non-heatwave periods.

Table 3 shows the estimated ORs of cause-specific mortality by age group during heatwave versus non-heatwave days. During heatwaves there was a statistically significant increase in the ORs for total mortality and mortality in the 75+ age group, total cardiovascular mortality and cardiovascular mortality in the 65–74 and 75+ age groups, and also for diabetes deaths in people aged 75+ after adjusting for the confounders humidity, PM_{10}, NO_2 and O_3. There was a striking, but not statistically significant, increase in respiratory mortality in the 15–64 age group. However, there was no statistically significant increase in the other mortality subgroups, even though the risk for most categories of deaths increased during heatwave periods.

Table 4 shows the estimated ORs for EHAs during heatwave versus non-heatwave days. The results for all cause EHAs were slightly different to those for mortality. During heatwaves there was a significant increase in total EHAs and in EHAs in those aged 65–74 and 75+, and also in total renal disease EHAs and renal disease EHAs in those aged 64–75, but no statistically significant increase in other age groups or for other diseases.

There were no real differences in the ORs between the different models (adjustment for humidity and O_3, adjustment for humidity and PM_{10}, adjustment for humidity and NO_2, and adjustment for humidity, PM_{10}, NO_2 and O_3) in both tables 3 and 4. We also evaluated the lagged effects (lag 1, lag 2 and lags 0–2 days) of heat on both mortality and EHAs from NEC (table 5). The lagged effects of heatwaves on mortality and EHAs were similar to those on the current day.

DISCUSSION

Three heatwaves (20–21 January 2000, 24–26 December 2001 and 21–22 February 2004) were identified between 1996 and 2005 in Brisbane, Australia. This study specifically investigated the heatwave–health relationship using information on temperature and cause-specific mortality and EHAs from NEC. People in Brisbane are acclimatised to hot summers which may reduce excess mortality and morbidity. However, our results show consistent and significantly increased risks of death and EHAs during heatwaves.

We used a time-stratified case–crossover analysis with a stratum length of 28 days. The main reason for using the case–crossover method was to control for seasonal confounders and secular trends. As there were only three heatwaves with a total of 7 case days and 21 control days, only 28 days were used in the final analysis (table 1). This did reduce the statistical power and meant that the CIs for some findings were wide (tables 3 and 4). Although a time series method would have used all the data, the time-stratified case–crossover and time series approaches are comparable.[26 27] Examination of heatwave versus non-heatwave days may mean estimates contain a combination of heat and heatwave effects. Hajat *et al*[7] discussed the concept of an added heatwave effect and evaluated whether heatwave days affected mortality risk differently than non-consecutive individual days of high temperatures. The additional effects of heatwaves have recently been estimated by first controlling for the general effects of heat and then estimating the extra burden of heatwaves.[14 15] This issue will be examined in our further research.

Total mortality and cardiovascular mortality significantly increased during heatwaves in Brisbane. This finding is consistent with most previous studies.[14 28] For example, Anderson and Bell[14] investigated the health impact of heatwaves in 43 US cities (1987–2005) and found higher mortality risk during heatwaves. Baccini *et al*[28] reported that high ambient temperatures have an important impact on European population health. This impact is likely to increase in the future, given the projected increase in mean temperatures and in the frequency, intensity and duration of heatwaves. However, we found a quite strong

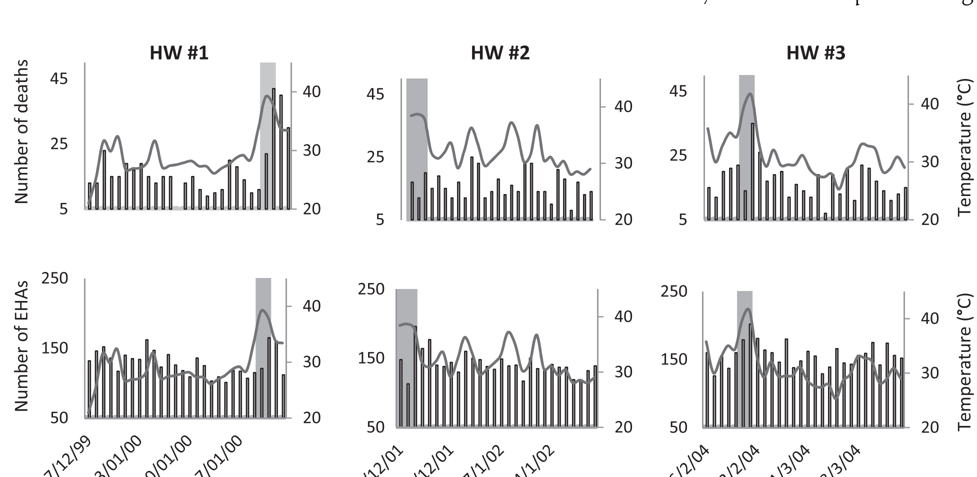

Figure 1 Maximum temperature associated with daily number of deaths and emergency hospital admissions (EHAs) from non-external causes during the three heatwaves by 28-day strata in Brisbane, Australia (the red curves represent maximum temperature, the bars denote deaths/EHAs on that day and the shaded bars represent heatwave periods). HW, heat wave.

Table 3 ORs of mortality during heatwaves in Brisbane

Deaths	Model I* OR (95% CI)	Model II† OR (95% CI)	Model III‡ OR (95% CI)	Model IV§ OR (95% CI)
NEC				
Aged 15–64	1.35 (0.80 to 2.26)	1.42 (0.84 to 2.38)	1.40 (0.83 to 2.35)	1.35 (0.80 to 2.27)
Aged 65–74	1.46 (0.89 to 2.39)	1.52 (0.92 to 2.48)	1.49 (0.91 to 2.43)	1.46 (0.89 to 2.39)
Aged 75+	**1.52 (1.21 to 1.91)**	**1.56 (1.24 to 1.95)**	**1.56 (1.24 to 1.95)**	**1.51 (1.20 to 1.90)**
Total	**1.47 (1.22 to 1.78)**	**1.52 (1.25 to 1.83)**	**1.51 (1.25 to 1.83)**	**1.46 (1.21 to 1.77)**
Cardiovascular				
Aged 15–64	1.61 (0.64 to 4.05)	1.69 (0.67 to 4.24)	1.67 (0.66 to 4.19)	1.63 (0.65 to 4.09)
Aged 65–74	**2.78 (1.20 to 6.45)**	**2.95 (1.28 to 6.83)**	**2.88 (1.25 to 6.66)**	**2.81 (1.21 to 6.51)**
Aged 75+	**1.86 (1.37 to 2.51)**	**1.88 (1.39 to 2.54)**	**1.88 (1.39 to 2.55)**	**1.83 (1.35 to 2.48)**
Total	**1.91 (1.46 to 2.50)**	**1.95 (1.49 to 2.56)**	**1.95 (1.49 to 2.55)**	**1.89 (1.44 to 2.48)**
Diabetes				
Aged 15–64	–¶	–	–	–
Aged 65–74	1.37 (0.12 to 15.40)	1.62 (0.15 to 18.10)	1.56 (0.14 to 17.36)	1.45 (0.13 to 16.44)
Aged 75+	9.49 (0.98 to 91.80)	**9.90 (1.02 to 95.68)**	**10.10 (1.04 to 97.95)**	**9.96 (1.02 to 96.85)**
Total	2.84 (0.71 to 11.45)	3.12 (0.78 to 12.52)	3.06 (0.76 to 12.31)	2.88 (0.71 to 11.62)
Ischaemic stroke				
Aged 15–64	–	–	–	–
Aged 65–74	–	–	–	–
Aged 75+	1.83 (0.30 to 11.05)	1.86 (0.31 to 11.20)	1.94 (0.32 to 11.68)	1.80 (0.30 to 10.89)
Total	1.85 (0.31 to 11.16)	1.92 (0.32 to 11.51)	1.98 (0.33 to 11.87)	1.83 (0.30 to 11.05)
Mental health				
Aged 15–64	–	–	–	–
Aged 65–74	–	–	–	–
Aged 75+	1.05 (0.27 to 4.10)	1.33 (0.34 to 5.16)	1.21 (0.31 to 4.72)	1.08 (0.27 to 4.23)
Total	0.80 (0.21 to 2.98)	1.04 (0.28 to 3.86)	0.92 (0.25 to 3.42)	0.82 (0.22 to 3.06)
Renal				
Aged 15–64	–	–	–	–
Aged 65–74	–	–	–	–
Aged 75+	0.87 (0.24 to 3.19)	0.90 (0.25 to 3.29)	0.85 (0.23 to 3.10)	0.86 (0.23 to 3.15)
Total	1.19 (0.37 to 3.82)	1.20 (0.38 to 3.84)	1.13 (0.35 to 3.63)	1.17 (0.37 to 3.78)
Respiratory				
Aged 15–64	7.72 (0.80 to 74.93)	8.63 (0.89 to 83.52)	8.87 (0.92 to 85.91)	8.25 (0.84 to 80.67)
Aged 65–74	2.69 (0.53 to 13.56)	2.84 (0.57 to 14.20)	3.04 (0.61 to 15.22)	2.78 (0.55 to 14.05)
Aged 75+	1.05 (0.49 to 2.25)	1.04 (0.49 to 2.24)	1.10 (0.51 to 2.35)	1.04 (0.48 to 2.23)
Total	1.47 (0.78 to 2.75)	1.49 (0.80 to 2.78)	1.55 (0.83 to 2.90)	1.45 (0.78 to 2.72)

*Adjusted for humidity and O_3.
†Adjusted for humidity and PM_{10}.
‡Adjusted for humidity and NO_2.
§Adjusted for humidity, PM_{10}, NO_2 and O_3.
¶Insufficient data.
NEC, non-external causes.

positive association between heatwave and respiratory mortality in younger people in this study (aged 15–64 years), although this did not reach statistical significance. This result is in contrast to previous research. For instance, D'Ippoliti *et al*[3] recently reported that the greatest effect of heatwaves was observed for elderly respiratory diseases in nine European cities. The reasons for the different results from this study and other reports are unclear. It may be because outdoor workers (eg, building and road construction) usually continue to work during heatwave periods in Brisbane, and can get sick or die from exposure to heat and high air pollution. However, this is only speculation, and no literature is available on this issue. We also found a higher mortality risk for elderly people (aged 75+ years) with diabetes, but we did not find similar results in other research and the underlying biological mechanism is not clear. The total number of deaths (64) during the first heatwave (20–21 January 2000) was greater than that for the other two heatwaves (49 in both the 2001 and 2004 heatwaves), although the maximum temperatures were not as high as during the latter two periods. This may be because the population was less prepared for the impact of the first heatwave or because the two more recent heatwaves occurred during a holiday season and at a weekend. Potential reasons include gradual improvements in housing, and the increased use of air conditioning and home insulation over recent years. For example, in 2008 about 50% of Queensland houses had insulation, up from 30% in 1994.[29]

NEC EHAs and those for renal disease increased during the heatwaves. As many statistical tests were conducted (tables 4 and 5), possible spurious significance from multiple testing for renal diseases cannot be ruled out. However, a number of studies have also investigated the impacts of heatwaves on cause-specific EHAs or emergency department visits, and our findings are generally consistent with those of other studies. For example, a study of EHAs in London[8] found an increase in respiratory and renal diseases among children under 5 years of age and in respiratory disease among people aged 75+, but failed to find statistically significant increases in total EHAs during extreme heat. Hansen *et al*[17] reported that there was a 10% increase in hospital admissions for all renal disease during heatwave periods in Adelaide, Australia, compared with non-heatwave periods in 2004. Age-specific analysis showed increases in renal hospital admissions across different age and sex groups, especially for

Table 4 ORs of emergency hospital admissions (EHAs) during heatwaves in Brisbane

EHAs	Model I* OR (95% CI)	Model II† OR (95% CI)	Model III‡ OR (95% CI)	Model IV§ OR (95% CI)
NEC				
Aged 15–64	0.97 (0.88 to 1.08)	0.98 (0.88 to 1.09)	0.99 (0.89 to 1.09)	0.97 (0.88 to 1.08)
Aged 65–74	**1.24 (1.02 to 1.51)**	**1.25 (1.03 to 1.52)**	**1.25 (1.03 to 1.52)**	**1.24 (1.02 to 1.50)**
Aged 75+	**1.40 (1.24 to 1.59)**	**1.43 (1.26 to 1.61)**	**1.43 (1.26 to 1.62)**	**1.39 (1.23 to 1.58)**
Total	**1.16 (1.08 to 1.24)**	**1.16 (1.09 to 1.25)**	**1.17 (1.10 to 1.26)**	**1.15 (1.07 to 1.23)**
Cardiovascular				
Aged 15–64	0.78 (0.55 to 109)	0.80 (0.57 to 1.12)	0.79 (0.56 to 1.11)	0.78 (0.55 to 1.09)
Aged 65–74	1.25 (0.86 to 1.83)	1.26 (0.86 to 1.84)	1.25 (0.86 to 1.83)	1.25 (0.86 to 1.83)
Aged 75+	1.14 (0.89 to 1.46)	1.17 (0.91 to 1.49)	1.16 (0.91 to 1.48)	1.14 (0.89 to 1.45)
Total	1.04 (0.87 to 1.24)	1.06 (0.89 to 1.26)	1.05 (0.88 to 1.25)	1.04 (0.87 to 1.23)
Diabetes				
Aged 15–64	1.04 (0.44 to 2.45)	0.98 (0.41 to 2.30)	1.00 (0.43 to 2.36)	1.03 (0.44 to 2.43)
Aged 65–74	1.37 (0.25 to 7.55)	1.43 (0.26 to 7.83)	1.50 (0.27 to 8.22)	1.35 (0.25 to 7.46)
Aged 75+	1.25 (0.48 to 3.28)	1.28 (0.49 to 3.34)	1.33 (0.51 to 3.46)	1.23 (0.47 to 3.22)
Total	1.21 (0.67 to 2.16)	1.18 (0.66 to 2.10)	1.21 (0.67 to 2.16)	1.20 (0.67 to 2.15)
Ischaemic stroke				
Aged 15–64	1.64 (0.30 to 9.06)	1.46 (0.27 to 7.98)	1.46 (0.27 to 7.99)	1.59 (0.29 to 8.80)
Aged 65–74	1.04 (0.21 to 5.17)	1.03 (0.21 to 5.11)	1.04 (0.21 to 5.14)	1.03 (0.21 to 5.10)
Aged 75+	0.41 (0.12 to 1.38)	0.40 (0.12 to 1.34)	0.41 (0.12 to 1.37)	0.41 (0.12 to 1.36)
Total	0.67 (0.30 to 1.52)	0.65 (0.29 to 1.47)	0.66 (0.29 to 1.49)	0.66 (0.29 to 1.50)
Mental health				
Aged 15–64	0.88 (0.71 to 1.11)	0.88 (0.70 to 1.10)	0.90 (0.72 to 1.12)	0.88 (0.71 to 1.11)
Aged 65–74	1.50 (0.45 to 4.99)	1.53 (0.46 to 5.08)	1.52 (0.46 to 5.05)	1.49 (0.45 to 4.98)
Aged 75+	0.60 (0.20 to 1.75)	0.59 (0.20 to 1.74)	0.60 (0.20 to 1.75)	0.59 (0.20 to 1.73)
Total	0.87 (0.70 to 1.08)	0.86 (0.70 to 1.07)	0.88 (0.71 to 1.09)	0.86 (0.70 to 1.07)
Renal				
Aged 15–64	1.17 (0.78 to 1.75)	1.17 (0.78 to 1.75)	1.20 (0.80 to 1.80)	1.16 (0.77 to 1.74)
Aged 65–74	**2.27 (1.06 to 4.86)**	**2.27 (1.06 to 4.86)**	**2.30 (1.07 to 4.93)**	**2.25 (1.05 to 4.83)**
Aged 75+	1.32 (0.86 to 2.04)	1.36 (0.88 to 2.08)	1.37 (0.89 to 2.10)	1.31 (0.85 to 2.02)
Total	**1.42 (1.09 to 1.84)**	**1.44 (1.11 to 1.86)**	**1.46 (1.13 to 1.89)**	**1.41 (1.09 to 1.83)**
Respiratory				
Aged 15–64	1.17 (0.82 to 1.67)	1.19 (0.83 to 1.69)	1.18 (0.83 to 1.69)	1.17 (0.82 to 1.67)
Aged 65–74	1.02 (0.60 to 1.75)	1.04 (0.61 to 1.78)	1.03 (0.60 to 1.77)	1.01 (0.59 to 1.74)
Aged 75+	1.33 (0.92 to 1.93)	1.37 (0.95 to 1.98)	1.39 (0.96 to 2.00)	1.33 (0.92 to 1.92)
Total	1.15 (0.95 to 1.40)	1.17 (0.96 to 1.43)	1.18 (0.97 to 1.43)	1.15 (0.94 to 1.40)

*Adjusted for humidity and O_3.
†Adjusted for humidity and PM_{10}.
‡Adjusted for humidity and NO_2.
§Adjusted for humidity, PM_{10}, NO_2 and O_3.
EHAs, emergency hospital admissions; NEC, non-external causes.

Table 5 ORs of mortality and EHAs during heatwaves in Brisbane for three different lags (days)

	Lag 1* OR (95% CI)	Lag 2* OR (95% CI)	Lags 0–2* OR (95% CI)
Deaths			
NEC	**1.48 (1.23 to 1.79)**	**1.51 (1.25 to 1.83)**	**1.46 (1.21 to 1.77)**
Cardiovascular	**2.01 (1.53 to 2.64)**	**2.06 (1.57 to 2.71)**	**1.89 (1.44 to 2.47)**
Diabetes	2.55 (0.63 to 10.26)	2.78 (0.69 to 11.19)	2.62 (0.65 to 10.59)
Ischaemic stroke	1.90 (0.32 to 11.49)	2.01 (0.33 to 12.07)	1.88 (0.31 to 11.34)
Mental health	1.16 (0.30 to 4.40)	1.13 (0.30 to 4.28)	0.92 (0.24 to 3.42)
Renal	1.12 (0.35 to 3.59)	1.17 (0.36 to 3.74)	1.14 (0.35 to 3.68)
Respiratory	1.47 (0.78 to 2.75)	1.48 (0.79 to 2.76)	1.44 (0.77 to 2.70)
EHAs			
NEC	**1.16 (1.08 to 1.24)**	**1.16 (1.09 to 1.25)**	**1.15 (1.08 to 1.24)**
Cardiovascular	1.04 (0.87 to 1.24)	1.03 (0.87 to 1.23)	1.05 (0.88 to 1.25)
Diabetes	1.13 (0.63 to 2.01)	1.11 (0.62 to 1.98)	1.17 (0.65 to 2.09)
Ischaemic stroke	0.64 (0.28 to 1.44)	0.62 (0.28 to 1.40)	0.67 (0.30 to 1.53)
Mental health	0.85 (0.69 to 1.06)	0.86 (0.70 to 1.07)	0.87 (0.70 to 1.08)
Renal	**1.45 (1.12 to 1.88)**	**1.46 (1.12 to 1.89)**	**1.40 (1.08 to 1.82)**
Respiratory	1.19 (0.98 to 1.45)	1.20 (0.99 to 1.47)	1.14 (0.93 to 1.38)

*Adjusted for humidity, PM_{10}, NO_2 and O_3.
EHAs, emergency hospital admissions; NEC, non-external causes.

elderly women. Another study[18] found that the 2006 California heatwave had a significant impact on morbidity, including in regions with relatively modest temperatures. The authors suggested that population acclimatisation and adaptive capacity influenced risk. Through better understanding of these impacts and population vulnerabilities, local communities can improve heatwave preparedness to cope with a warmer future.

Recent publications using different heatwave definitions have reported inconsistent results regarding heat-related mortality. For example, the study by Anderson and Bell[13] reported that comparison of the 99th and 90th percentile temperatures for cities in the USA showed that heat-related mortality was mostly associated with a shorter lag (average of same day and previous day), with an average increase of 3.0% in mortality risk (95% posterior interval: 2.4% to 3.6%). Hajat *et al*[7] observed the impact of high temperatures on mortality in three European cities. They used a combination of intensity and duration to define heatwave periods and found that heatwave effects were apparent in simple time-series models but were small when compared with the overall summertime mortality burden of heat. However, another study[21] used 3 or more consecutive days with a daily maximum temperature above 35°C as a heatwave definition and found no excess mortality during heatwaves in Adelaide, Australia (located at 34°52′S, 138°30′E).

Our previous study indicates that even a small change in the heatwave definition had an appreciable effect on the estimated health impact.[10] In order to conduct a sensitivity analysis, we used some less stringent definitions of heatwave to estimate the effects on both mortality and EHAs from NEC in the same study period (1996–2005). Thirty-six heatwaves (95 days) and nine heatwaves (20 days) were identified by the definitions of heatwave as a daily maximum temperature of at least 33°C or 35°C for two or more consecutive days, respectively. The longest heatwave periods were 5 days in January 2000 and February 2004 (33°C for 2 or more consecutive days). There were statistically significant increases in NEC mortality (ORs 1.11 and 1.26) and for those aged 75+ (ORs 1.11 and 1.29) by these two different definitions (33°C or 35°C for 2 or more consecutive days). Similar results were also found for EHAs. It appears that the more stringent the definitions of heatwave, the greater the estimates of its effects.

We found that elderly people were most vulnerable to developing, and dying from, heat-related illnesses during a heatwave, which is consistent with previous studies, and is likely to be related to overload of the thermoregulatory system in older people.[9 30 31] A recent study[30] revealed the effects of the ageing process on thermoregulatory responses and outlined the symptoms of heat exhaustion and heatstroke among the elderly. Another study[31] observed that the elderly had poor thermoregulatory responses to high temperatures because of hormonal changes with age.

In order to determine if there were any short-term delays between heatwave and health outcomes, the effects of lags 1, 2 and 0–2 days were examined after adjusting for humidity, PM_{10}, NO_2 and O_3. The results show that statistically significant lagged effects of heatwave were found for total mortality and EHAs (NEC), cardiovascular mortality and renal EHAs (table 5).

This study has three major strengths: (1) this is the first study to broadly examine heat-related health effects including cause-specific mortality and EHAs in a subtropical setting; (2) the dataset used in this study was comprehensive; and (3) importantly, we were able to adjust for the possible confounding effects of air pollution and humidity.

This study has some limitations. First, it focused on only one city. However, the finding of consistent patterns of mortality and EHAs during heatwaves may inspire further research in other locations. Second, we only considered the effect of heatwaves on mortality and EHAs using aggregated data. Individual exposure and outcome data would give a more accurate estimate of the dangers of heat, but these detailed data were not available. Finally, as we focused on extreme heatwave events we had a greatly reduced dataset and hence statistical power. However, many statistically significant associations were found in this study, which suggest the areas for more attention when preparing for heatwave response.

CONCLUSION

A significant increase in mortality and EHAs from NEC was observed during three short-lasting heatwaves in Brisbane, a subtropical city where people are well accustomed to warm weather. The elderly and those with cardiovascular, renal or diabetic disease appeared to be particularly vulnerable. The findings from this study have implications for understanding heat-related health effects and contribute to the development of an evidence base for public health intervention strategies to prevent and mitigate the impact of heatwaves. Based on this study, more specific intervention strategies appear warranted such as targeting the elderly (aged ≥75 years) and those with cardiovascular, renal or diabetic disease. Brisbane does not have a formal public health prevention plan for heatwaves. Therefore it is important for local governments to develop appropriate response plans to cope with the increasing threat from heatwaves.

Acknowledgements We thank Queensland Health, the Environmental Protection Agency, the Office of Economic and Statistical Research of the Queensland Treasury, and the Australia Bureau of Meteorology for providing the relevant data.

Funding This study was partly funded by the Australian Research Council (LP882699), the Queensland Department of Environment and Resources Management, Community Safety, Queensland Health and the Environmental Protection Agency. ST was supported by an NHMRC research fellowship (#553043). PA was partially supported by a Noel Stevenson Fellowship from the Queensland Emergency Medicine Research Foundation (QEMRF).

Competing interests None.

Provenance and peer review Not commissioned; externally peer reviewed.

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Occup Environ Med 2012 69: 163-169 originally published online June 30, 2011
doi: 10.1136/oem.2010.062141