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Heatwave and health events: A systematic evaluation of different temperature indicators, heatwave intensities and durations

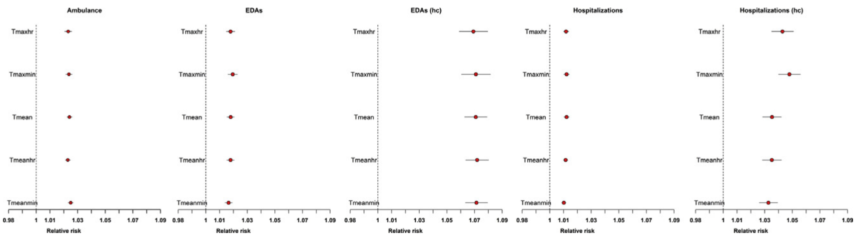
Zhiwei Xu [a,*], Jian Cheng [a], Wenbiao Hu [a], Shilu Tong [a,b,c,**]

[a] *School of Public Health and Social Work & Institute of Health and Biomedical Innovation, Queensland University of Technology, Australia*
[b] *School of Public Health and Institute of Environment and Human Health, Anhui Medical University, Hefei, China*
[c] *Shanghai Children's Medical Centre, Shanghai Jiao-Tong University, Shanghai, China*

HIGHLIGHTS

- Mean temperature was slightly better than maximum temperature in predicting heatwave-related morbidity.
- When heatwave intensity was not high (≤93th percentile), two-day-duration heatwaves were more detrimental than longer-lasting heatwaves.
- There was a relatively consistent temperature trigger (97th percentile).
- Ambulance service uses were more sensitive to heatwaves than other health outcomes.

GRAPHICAL ABSTRACT



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ABSTRACT

Objectives: Temperature observation time and type influenced the assessment of heat impact on mortality, and different health events may have different temperature thresholds beyond which these health events increase substantially. This study aimed to investigate whether temperature observation time and type influenced the assessment of heatwave impact on morbidity, to assess how heatwave duration modified heatwave impact on morbidity, and to examine whether there was a consistent temperature threshold beyond which five different types of health events increased sharply.

Methods: Minutely air temperature data in Brisbane, Australia, were collected and converted into five daily temperature indicators observed at different time points or calculated using different approaches. Twenty-nine heatwave definitions for each temperature indicator were used to examine the effects of heatwaves on five health events (i.e., ambulance service uses, emergency department attendances (EDAs), hospitalizations, possible EDAs of heat and/or dehydration, and possible hospitalizations of heat and/or dehydration) by quasi-Poisson models.

Results: Mean temperature was slightly better than maximum temperature in predicting heatwave impact on morbidity ($P < 0.05$), and no appreciable difference in model performance was observed amongst different mean temperature indicators. Two-day-duration heatwaves were more detrimental than longer-lasting heatwaves when heatwave intensity was not high, and 97th percentile appeared to be a consistent temperature threshold for most heatwave-related health events ($P < 0.05$).

Conclusions: It seems desirable in the development of heatwave definition and early warning systems to use mean temperature as an exposure indicator, and to adopt the 97th percentile of temperature as the trigger in Brisbane. Health sectors need to better prepare for short-lasting heatwaves.

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* Correspondence to: Z. Xu, School of Public Health and Social Work& Institute of Health and Biomedical Innovation, Queensland University of Technology, Kelvin Grove 4059, Australia.
** Correspondence to: S. Tong, Department of Clinical Epidemiology and Biostatistics, Shanghai Children's Medical Centre, Shanghai Jiao-Tong University, Shanghai 200127, China.
E-mail addresses: xzw1011@gmail.com (Z. Xu), shilu.tong@yahoo.com (S. Tong).

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1. Introduction

The health impact of heatwaves has been extensively documented (Anderson and Bell, 2011; Gasparrini and Armstrong, 2011; Li et al., 2015; Xu et al., 2016). The frequency of heatwaves has increased in Europe, China and Australia (IPCC, 2014), and as projected, heatwaves will be more frequent, more intense, and longer-lasting in the future (Meehl and Tebaldi, 2004), raising the concern about increasing health burden due to heatwaves in the context of climate change (Huang et al., 2011).

Heatwave-related health burden can be largely relieved by effective heat action plan which includes heatwave early warning and emergency public health measures (Benmarhnia et al., 2016; McGregor et al., 2015; Toloo et al., 2013). A big constrain of developing heatwave early warning systems is that there is no widespread consensus on how to define a heatwave and previous research suggested that a slight change in heatwave definition may cause an appreciable difference in the estimated health effects in Brisbane, Australia (Tong et al., 2010). This finding has also been observed in Nanjing, China, and Alabama, the US (Chen et al., 2015; Kent et al., 2014).

Existing heatwave definitions vary in three aspects, i.e., temperature indicator, heatwave duration and intensity (Xu et al., 2016). Some studies used maximum temperature to define heatwaves as it reflects the peak temperature level (Basagaña et al., 2011; Sun et al., 2014b; Wang et al., 2012), while others adopted mean temperature because it may better represent the temperature exposure across a whole day (Anderson and Bell, 2011; Gasparrini and Armstrong, 2011; Zeng et al., 2014). Minimum temperature has also been used in Paris (France), and Switzerland (Laaidi et al., 2012; Ragettli et al., 2017), and Barnett et al. have found that no one temperature indicator was superior to others in the US (Barnett et al., 2010). Davis et al. observed that, in seven US cities, temperature observed at different time points or calculated using different methods influenced the estimates of heat-related mortality (Davis et al., 2016). So far, it remains unclear what is the best predictor of heatwave-related health impact, and whether temperature observation time affects the estimation of heatwave-related health risks.

Hajat et al. argued that the health impact of heatwaves is composed of two components, i.e., the independent effect due to daily ambient high temperature (main effect), and the added effect due to sustained period (i.e., duration) of heat (added effect) (Hajat et al., 2006). Some studies have found a significant added effect of heatwaves on mortality (Hajat et al., 2006; Tong et al., 2014), but other studies found inconsistent results across different cities (Anderson and Bell, 2011; Zeng et al., 2014). Gasparrini and Armstrong reported that the added effect of heatwaves on mortality was much smaller or even negligible compared with the main effect (Gasparrini and Armstrong, 2011). The characteristics of the relationship between heatwave duration and morbidity may be different from the relationship between heatwave duration and mortality, because people may quickly seek medical help once heatwave starts (e.g., 2 days) and triggers health problems. However, there is a dearth of literature on whether/how heatwave duration modified its impact on morbidity (Kent et al., 2014).

For the development of tailored and cost-effective heat early warning systems, it is of great importance to understand the temperature threshold beyond which the health impact of heatwave increase sharply/alarmingly (Xu et al., 2016). An extremely high temperature threshold (e.g., 99th percentile of temperature) may not protect people in a timely manner and a very low temperature threshold may trigger early warning systems too frequently, wasting health resources and making the public bored. The effect of heatwave on mortality increased with the increase of heatwave intensity in three Australian cities (Tong et al., 2015), but in Nanjing, China, heatwave effect on mortality decreased when its intensity increased from 98th percentile to 99th percentile (Chen et al., 2015). In Houston, the US, the relationship between heatwave intensity increase and the change in its health impact varied across different age groups and health outcomes (i.e., mortality and emergency department visits) (Zhang et al., 2015). Petitti et al. reported that in Maricopa County, the US, the temperature thresholds which triggered health issues varied according to the health events analyzed (Petitti et al., 2016). To the best of our knowledge, no study has elucidated the best heatwave intensity cut-off point for heatwave definition or early warning using a series of health outcomes.

The present study used the data on ambulance service uses (ASUs), emergency department attendances (EDAs), and hospitalizations in Brisbane, Australia, aiming to fill the above mentioned research gaps and address four research questions: i). Which temperature indicator performed the best in predicting heatwave-health events in Brisbane? ii). Did different health events increase with the increase of heatwave duration in Brisbane? iii). Which temperature intensity should be adopted for developing a proper heatwave definition and triggering a heatwave early warning? and iv). Whether there was any heterogeneity in heatwave sensitivity across different health events? The fundamental motivation behind this study was not to develop a heatwave definition which can be applied to all regions in the world as that is hard (if not impossible) at this stage, but to explore a way to develop a proper heatwave definition in Brisbane (and possibly other cities of similar climate/socioeconomic status) and call for attention to be paid to adopting evidence-based temperature indicator, temperature threshold, and heatwave duration in the development of a locally-suitable heatwave definition in other regions of the world.

2. Materials and methods

2.1. Study setting

Brisbane is the capital city of Queensland, and it locates on the east coast of Australia (27° 30′S, 153° 00′E). It is the third biggest city of Australia and its population in 2011 was 197.7 million. It has a subtropical climate, with a general trend of hot summers and mild winters.

2.2. Data collection

Data on daily ASUs in summer seasons (1st December 2008 to 28th February 2015), EDAs (1st January 2013 to 31st December 2015), and hospitalizations (1st January 2005 to 31st December 2015) in Brisbane were obtained from Queensland Health. Petitti et al. introduced a category of health conditions which are possible consequences of heat and/or dehydration when they examined the health impact of high temperature (Petitti et al., 2016). We extracted the data on these health consequences of heat and/or dehydration (https://ehp.niehs.nih.gov/wp-content/uploads/124/2/ehp.1409119.s001.acco.pdf) from the datasets of EDAs and hospitalizations in Brisbane according to the corresponding International Classification of Diseases 10th Revision codes (ICD-code 10) and analyzed them as another two types of health events (EDAs (hc), and hospitalizations (hc)). The diagnoses of patients using ambulance service were vague and thus we did not extract the health consequences of heat and/or dehydration from the ASUs dataset. Mortality, and heat-related EDAs and hospitalizations (e.g., heat stroke and heat syncope, etc.) were not investigated in this study as they have been analyzed in our prior works (Toloo et al., 2014; Tong et al., 2015; Tong et al., 2014). Therefore, in total, there were five health events in the present study: ASUs, all-cause EDAs, EDAs (hc), all-cause hospitalizations, and hospitalizations (hc).

Whether daily mean temperature should be calculated by simply averaging maximum and minimum temperatures when examining the health impact of heatwaves is a concern of research community. Davis et al. reported that temperature observation time and type influenced the assessment of high temperature and mortality relationship (Davis et al., 2016). We collected data on air temperature by minute from 1st January 2005 to 31st December 2015 from Australian Bureau of Meteorology, and converted the data into daily data on maximum and mean temperatures using different calculation methods to examine whether temperature observation time and type influenced the impact of heatwaves on morbidity. The data were originally collected from one monitoring station nearby Brisbane airport, and our previous work has found that using one-station data or multi-station data did not differ in quantifying the health impact of high temperature (Guo et al., 2013). Specifically, there were five types of temperature indicators in the present study. First, maximum temperature between midnight and midnight which could occur at any minute (T_{maxmin}); second, maximum temperature of 24 hourly values observed at each hour (e.g., 3:00 pm) (T_{maxhr}); third, mean temperature which was averaged by all values observed at every minute across a whole day ($T_{meanmin}$); forth, mean temperature which was averaged by 24 hourly temperature values (T_{meanhr}); and fifth, mean temperature which was averaged by daily maximum temperature (T_{maxmin}) and minimum temperature (T_{minmin}) which can occur at any minute (T_{mean}). In total, we used five temperature indicators to define heatwave: T_{maxhr}, T_{maxmin}, T_{mean}, T_{meanhr}, and $T_{meanmin}$. Similar information on these temperature indicators can also be found in Petitti et al.'s paper (Petitti et al., 2016).

Data on daily average particulate matter ≤10 μm (PM_{10}) (μg/m^3), and daily average nitrogen dioxide (NO_2) (μg/m^3) from 1st January 2005 to 31st December 2015 were obtained from the Queensland Department of Environment and Heritage Protection. The air pollution data were initially collected from two monitoring stations (i.e., Brisbane CBD station, and Brisbane Rocklea station). Ethical approval (approval number: 1500000369) was obtained from the Queensland University of Technology Human Research Ethics Committee before the data were collected.

2.3. Heatwave definitions

Heatwave was defined by incorporating temperature indicators, heatwave duration and intensity. For heatwave duration, we adopted the most commonly used three durations (i.e., ≥2, 3 or 4 consecutive days) (Xu et al., 2016). To fully investigate whether/how heatwave intensity modified heatwave impact on morbidity, and to explore which heatwave intensity should be used for heatwave definition and early warning, we adopted 10 heatwave intensities (i.e., 90th percentile, 91th percentile, …, and 99th percentile). As the most intense heatwave (i.e., 99th percentile for 4 days) did not occur in Brisbane from 2005 to 2015, 29 heatwave definitions for each temperature indicator were used in the final analysis. The detailed information on these heatwave definitions, the corresponding temperature values and the number of heatwaves days from 2005 to 2015 was delineated in Table 1. As the time periods which different health event datasets covered were variable, we calculated heatwave periods from 1st January 2005 to 31st December 2015 at the first stage using temperature data and then merged the heatwave datasets with health event datasets according to the time period of each health event dataset.

2.4. Data analysis

A quasi-Poisson generalized additive model was used to assess the effects of heatwaves on five health events (Xu et al., 2017). As heatwave effects on health events may occur not just on the day of exposure but also few days after (Anderson and Bell, 2009; Li et al., 2015), we used a distributed lag non-linear model to capture the lag effect (Gasparrini et al., 2010). Seven days were used as the lag period as we did some pilot analyses and found the longest effect lasted for approximately a week, and prior studies also observed the similar lag period (Li et al., 2015). PM_{10}, NO_2, day of week, seasonality and long-term trend were controlled for as potential confounders. A natural cubic spline with eight degrees of freedom (*df*s) was used to control for the seasonality and long-term trend for EDAs, EDAs (hc), hospitalizations, and hospitalizations (hc). A natural cubic spline with three *df*s was used to control for with-in season variation and long-term trend for ASUs as only summer season data for ASUs were available. Day of week was controlled for as a dummy variable. These *df*s were chosen based on the minimum generalized cross validation (GCV).

To investigate which temperature indicator was the best predictor of heatwave-related health events, we compared GCVs of the models produced by the five temperature indicators using one way analysis of variance (ANOVA). To assess whether the effects of heatwaves on five health events increased with the increase of heatwave duration or intensity, we meta-analyzed the effects of heatwaves on five health events under each heatwave duration and intensity. Meta-regressions were also done to examine whether the differences in the effects of heatwaves on five health events were statistically significant across different heatwave durations and intensities.

All analyses were conducted in R (version 3.2.2), with "mgcv" and "dlnm" to conduct generalized additive model and distributed lag non-linear model (Gasparrini et al., 2010). Meta-analysis and meta-regression were performed using the "metafor" package (Wu et al., 2013).

3. Results

Table 2 shows the descriptive statistics of maximum, mean, and minimum temperatures. The average value of T_{maxmin} (26.3 °C) was greater than T_{maxhr} (25.7 °C), and the average value of T_{meanhr} (21.9 °C) was greater than T_{mean} (21.3 °C) and $T_{meanmin}$ (20.7 °C). The daily mean numbers of ASUs, EDAs, EDAs (hc), hospitalizations, and hospitalizations (hc) were 705.2, 1116.0, 60.3, 484.0, and 13.6, respectively. Table 3 indicates the correlation coefficients amongst different temperature indicators. The correlation between T_{mean} and T_{meanhr} ($r = 0.998$) was the greatest, followed by the correlation between T_{maxmin} and T_{maxhr} ($r = 0.993$). $T_{meanmin}$ had the relatively weakest correlation with other temperature indicators.

Fig. 1 shows the effects of heatwaves on ASUs and Figs. S1a to S1d (supplementary material) show the effects of heatwaves on the other four health events, suggesting that two-day-duration heatwave had greater effects on five health events when heatwave intensity was not very high (≤93th percentile, i.e., hw1 to hw12), although heterogeneity existed for ASUs (Fig. 1). For high-intensity heatwaves (≥97th percentile, i.e., hw22 and onwards), the confidence intervals of heatwave effect were wider because of low frequency of these heatwaves. From 2005 to 2015, Brisbane did not experience extremely high intense heatwaves (e.g., 98th percentile of maximum temperature & 3 days, i.e., hw 26), and therefore the information on the health effects of these heatwaves was missing in Figs. 1 and Figs. S1a to S1d.

Fig. 2 reveals the performance of models produced by five different temperature indicators. The one way ANOVA results suggest that mean temperature was slightly better than maximum temperature for assessing heatwave effects on ASUs and EDAs (hc), and no statistical difference was observed amongst three mean temperature indicators. Fig. 3 shows the pooled effects of heatwaves on five health events, revealing that the magnitudes of heatwave effects produced by five temperature indicators were quite similar, although heatwave effects on hospitalizations (hc) produced by maximum temperature were slightly greater than mean temperature. Fig. 3 also reveals that ASUs were more sensitive to heatwaves than EDAs and hospitalization. Not surprisingly, the consequences of heat and/or dehydration (EDA (hc) and hospitalizations (hc)) increased more than the other three health events.

Based on the findings of Figs. 2 and 3, we presented the results produced from the models of T_{mean} (the temperature indicator which can most easily be calculated in practice) in Figs. 4 and 5. Fig. 4 shows the pooled effects of heatwaves on five health events under three different heatwave durations, suggesting that two-day-duration heatwaves tended to have greater effects on most health events when heatwave intensity was moderate. Figs. S2a to S2d (supplementary material) which display the results for other four temperature indicators also show the same pattern. Fig. 5 shows the pooled effects of heatwaves on five health events under 10 temperature intensities. Figs. S3a and S3d

Table 1
Heatwave definitions used in this study.

Heatwave types	Specific definitions	Tmaxhr		Tmaxmin		Tmeanhr		Tmeanmin		Tmean	
		M	N	M	N	M	N	M	N	M	N
hw1	90th percentile & 2 days	30.3	290	30.9	281	25.9	342	25.6	356	26.1	338
hw2	90th percentile & 3 days	30.3	206	30.9	177	25.9	268	25.6	304	26.1	266
hw3	90th percentile & 4 days	30.3	131	30.9	117	25.9	220	25.6	229	26.1	206
hw4	91th percentile & 2 days	30.4	261	31.1	261	26.1	316	25.8	329	26.3	294
hw5	91th percentile & 3 days	30.4	175	31.1	169	26.1	244	25.8	267	26.3	222
hw6	91th percentile & 4 days	30.4	121	31.1	112	26.1	196	25.8	201	26.3	168
hw7	92th percentile & 2 days	30.6	221	31.2	208	26.3	277	25.9	271	26.5	277
hw8	92th percentile & 3 days	30.6	147	31.2	124	26.3	205	25.9	213	26.5	211
hw9	92th percentile & 4 days	30.6	102	31.2	70	26.3	163	25.9	168	26.5	160
hw10	93th percentile & 2 days	30.9	175	31.5	171	26.5	213	26.1	228	26.6	228
hw11	93th percentile & 3 days	30.9	101	31.5	103	26.5	157	26.1	182	26.6	172
hw12	93th percentile & 4 days	30.9	68	31.5	67	26.5	115	26.1	137	26.6	127
hw13	94th percentile & 2 days	31.2	147	31.7	135	26.6	174	26.3	191	26.8	180
hw14	94th percentile & 3 days	31.2	81	31.7	83	26.6	128	26.3	147	26.8	130
hw15	94th percentile & 4 days	31.2	54	31.7	50	26.6	95	26.3	111	26.8	100
hw16	95th percentile & 2 days	31.5	120	32.1	114	26.9	138	26.5	162	27.0	136
hw17	95th percentile & 3 days	31.5	64	32.1	62	26.9	98	26.5	114	27.0	92
hw18	95th percentile & 4 days	31.5	46	32.1	29	26.9	62	26.5	84	27.0	62
hw19	96th percentile & 2 days	31.9	77	32.4	82	27.2	99	26.7	129	27.3	108
hw20	96th percentile & 3 days	31.9	33	32.4	38	27.2	53	26.7	89	27.3	72
hw21	96th percentile & 4 days	31.9	12	32.4	20	27.2	41	26.7	50	27.3	42
hw22	97th percentile & 2 days	32.3	41	32.9	49	27.5	67	27.0	84	27.7	71
hw23	97th percentile & 3 days	32.3	13	32.9	13	27.5	35	27.0	44	27.7	31
hw24	97th percentile & 4 days	32.3	4	32.9	4	27.5	26	27.0	32	27.7	22
hw25	98th percentile & 2 days	32.9	27	33.4	25	28.0	41	27.4	44	28.2	35
hw26	98th percentile & 3 days	32.9	3	33.4	3	28.0	25	27.4	26	28.2	19
hw27	98th percentile & 4 days	32.9	0	33.4	0	28.0	13	27.4	17	28.2	13
hw28	99th percentile & 2 days	33.9	4	34.4	4	28.6	17	28.0	23	28.8	13
hw29	99th percentile & 3 days	33.9	0	34.4	0	28.6	7	28.0	7	28.8	3

hw, heatwave; M, mean value of temperature; N, number of heatwave days under this heatwave definition from 2005 to 2015.
Tmaxhr, the maximum value of hourly temperatures across the whole day;
Tmaxmin, the maximum value of temperatures recorded by every minute across the whole day;
Tminhr, the minimum value of hourly temperatures across the whole day;
Tminmin, the minimum value of temperatures recorded by every minute across the whole day;
Tmeanhr, the mean value of hourly temperatures across the whole day;
Tmeanmin, the mean value of temperatures recorded by every minute across the whole day;
Tmean, (Tmaxmin+Tminmin)/2;

present the pooled effects of heatwaves on five health events under 10 intensities for other four temperature indicators. To further explore whether the greater effects of two-day-duration heatwaves (or more intense heatwaves) on most health events were because of its earlier occurrence (people might be less adapted to early season heatwaves), we looked at the timing of occurrence of each heatwave and found more intense heatwaves were more likely to occur in early summer (Table S1).

Table 4 presents the meta-regression results for T_{mean}, revealing that when heatwave intensity increased from 90th percentile to 97th percentile, ASUs increased significantly, and when heatwave intensity increased from 90th percentile to 98th percentile, hospitalizations increased significantly. Hospitalizations (hc) increased significantly when heatwave intensity increased from 90th percentile to 99th percentile. Table S2 (supplementary material) presents the results for other four temperature indicators, and these results also suggest that two-day-duration heatwaves were more detrimental to health when heatwave intensity was not high. In terms of the specific heatwave intensity beyond which ASUs and hospitalization (or hospitalizations

Table 2
Summary statistics of daily temperature indicators and health events in Brisbane from 1st January 2005 to 31st December 2015.

	Range	Mean	Percentile	
			25	75
T_{maxhr} (°C)	11.7–38.5	25.7	22.8	28.5
T_{maxmin} (°C)	13.0–40.1	26.3	23.4	29.1
T_{meanhr} (°C)	9.7–34.3	21.9	17.8	24.2
$T_{meanmin}$ (°C)	10.4–30.1	20.7	17.4	24.0
T_{mean} (°C)	10.7–31.5	21.3	18.0	24.5
T_{minhr} (°C)	3.1–34.3	16.5	13.0	20.2
T_{minmin} (°C)	2.7–26.1	16.2	12.7	20.0
Ambulance service uses (ASUs) (2008–2015)	492–992	705.2	623	784
Emergency department attendances (EDAs) (2013–2015)	531–931	668.1	624	704
Emergency department attendances (EDAs) (hc) (2013–2015)	31–98	60.3	53	67
Hospitalizations (2005–2015)	228–813	484.0	387	586
Hospitalizations (hc) (2005–2015)	1–35	13.6	10	17

Tmaxhr, the maximum value of hourly temperatures across the whole day;
Tmaxmin, the maximum value of temperatures recorded by every minute across the whole day;
Tminhr, the minimum value of hourly temperatures across the whole day;
Tminmin, the minimum value of temperatures recorded by every minute across the whole day;
Tmeanhr, the mean value of hourly temperatures across the whole day;
Tmeanmin, the mean value of temperatures recorded by every minute across the whole day;
Tmean, (Tmaxmin+Tminmin)/2;
hc, heat consequences.

Table 3
The Spearman's correlation coefficients between temperature indicators.

	T_{maxhr}	T_{maxmin}	T_{meanhr}	$T_{meanmin}$
T_{maxmin}	0.993			
T_{meanhr}	0.931	0.931		
$T_{meanmin}$	0.919	0.922	0.990	
T_{mean}	0.927	0.933	0.998	0.990

For all correlations, $P < 0.001$.

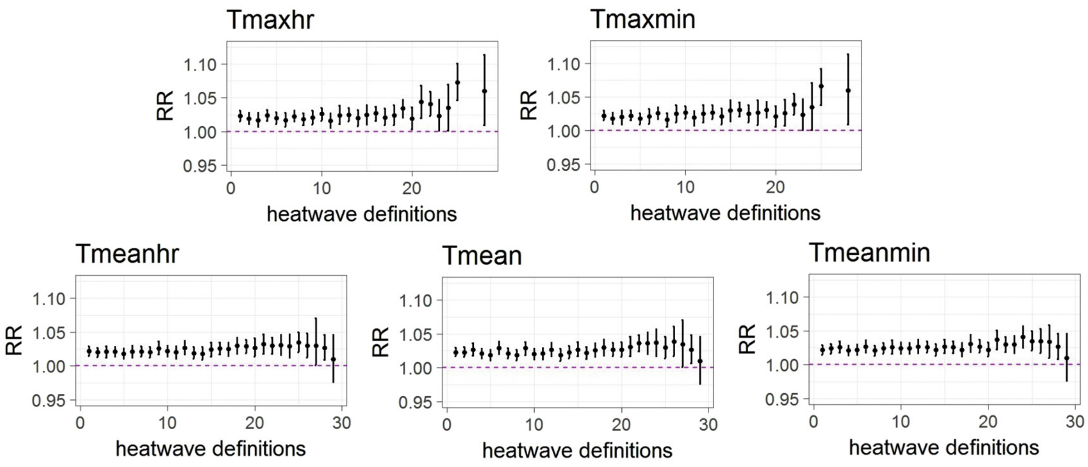


Fig. 1. Heatwave and ambulance service uses (RR: relative risk).

(hc)) increased sharply, heterogeneity existed across different temperature indicators, but 97th percentile appeared to be a relatively consistent cut-off point, particularly for ASUs and hospitalizations (hc). For all temperature indicators, EDAs and EDAs (hc) did not increase sharply when heatwave intensity increased from 90th percentile to other higher percentiles.

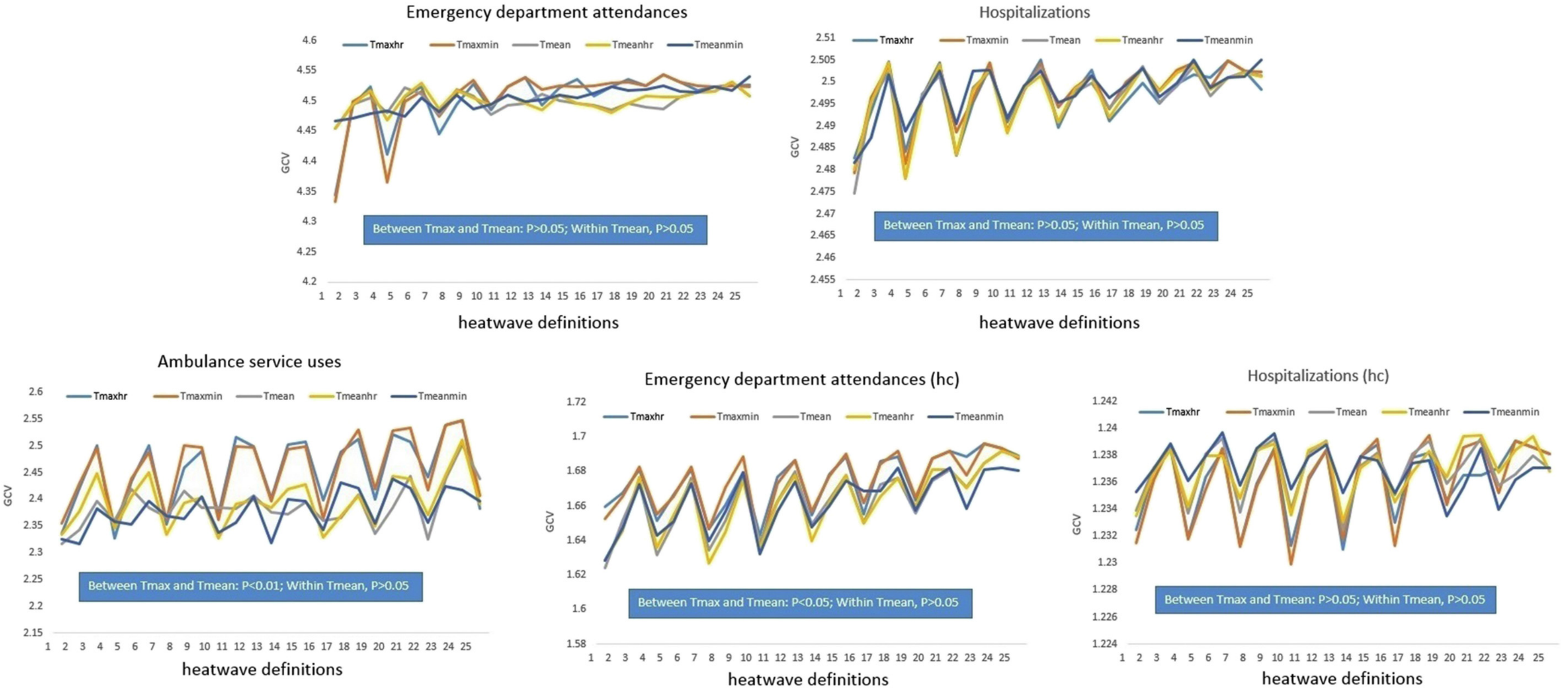
4. Discussion

The present study yielded four major findings: i). Mean temperature performed slightly better than maximum temperature in predicting the impact of heatwave on morbidity; ii). When heatwave intensity was not high, two-day-duration heatwaves had a greater impact on morbidity than longer-lasting heatwaves; iii). When heatwave intensity increased from 90th percentile to 97th percentile, ASUs, hospitalizations, and hospitalizations (hc) increased substantially; and iv). ASUs were more sensitive to heatwaves, followed by EDAs and hospitalizations.

Maximum temperature has been widely used as the temperature indicator for heatwave definition (Basagaña et al., 2011; Sun et al., 2014b; Wang et al., 2012) as it approximates the maximum thermal stress on the body (Tan et al., 2007). However, Laaidi et al. found that in Paris, high minimum temperature at night significantly increased the probability of death in elderly people during a heatwave and daytime temperature was found less important (Laaidi et al., 2012), highlighting the importance of nighttime respite for the body to recover during heatwave periods (Basu and Samet, 2002) and indicating the necessity of adopting mean temperature which combines maximum temperature and minimum temperature within a day. The present study found that mean temperature was slightly better than maximum temperature in predicting the association between heatwave and morbidity (Fig. 2), echoing to our prior findings on the optimal temperature indicator for the heatwave and mortality relationship in Brisbane (Xu and Tong, 2017). There are two commonly used ways to examine which temperature indicator can better predict the association between temperature and health event, i.e., the magnitude of relative risk (RR) (Chen et al., 2017), and model fit parameters such as Akaike information criterion (AIC) (Yu et al., 2011) and GCV (Davis et al., 2016). RR estimation is largely based on the comparison between one temperature value (e.g., 98th percentile) and a reference temperature value, and GCV takes the entire temperature distribution into account, and thus GCV is relatively more reliable. In the present study, the estimated RR values of maximum temperature models for hospitalizations (hc) were higher than the RR values of mean temperature models (Fig. 3), which is slightly different from the findings of Fig. 2. This difference may be caused by a small number of highly influential data points. Ideally, both RR (point estimate and the width of confidence interval) and model fit parameters need to be used in the future studies attempting to assess the optimal temperature indicator for heatwave definition and early warning.

Temperature observed at different time points within a day (e.g., T_{maxhr} and T_{maxmin}), and temperature calculated using different methods (e.g., $T_{meanmin}$ and T_{mean}) may represent different thermal exposure levels because the pattern of daily warming and cooling is not consistent (Davis et al., 2016). In this study, we found that, in general, characteristics of the relationship between heatwave and health events (e.g., magnitude of RRs and patterns of this relationship across different heatwave durations and intensities) produced by T_{maxhr} and T_{maxmin} models (Fig. 1 and Figs. S1a to S1d) largely aligned with each other, and so did T_{meanhr} (calculated by 24 values) and T_{mean} (calculated by two values), although there was minor heterogeneity in the width of confidence interval for estimated RRs which may be attributable to the small number of extreme heatwaves. Compared with T_{meanhr} and T_{mean}, $T_{meanmin}$ was calculated using more number of values (1440) each day and the characteristics of the relationship between intense heatwaves (e.g., 97th and 98th percentiles) and health events produced by $T_{meanmin}$ were different from that of T_{meanhr} and T_{mean} (Fig. 1 and Figs. S1a to S1d). Whether $T_{meanmin}$ over smoothed temperature exposure during heatwaves or not remains unclear so far, and it needs to be unveiled by looking at how different subgroups (e.g., different age groups and different genders) react to $T_{meanmin}$ heatwaves and T_{mean} heatwaves. Based on the similar results of T_{meanhr} and T_{mean} models, we think that in the future, calculating mean temperature by simply averaging maximum temperature and minimum temperature is appropriate.

Interestingly, we found that two-day-duration heatwaves were associated with a greater increase in morbidity compared with longer-lasting heatwaves, when heatwave intensity was not high (≤93th percentile). Available evidence documented that heatwaves occurred in early summer may be more detrimental than heatwaves in late summer (Gasparrini et al., 2016; Ragettli et al., 2017), but this may not explain the finding in our study as we did not find that two-day-duration heatwaves occurred more in early summer (Table S1). Sun et al. have also observed that in Shanghai, China, emergency department visits increased more during two-day-duration heatwaves than three-day-duration heatwaves when heatwave intensity was above 90th percentile (Sun et al., 2014a). Previous studies looking at how heatwave duration modified its health impact predominantly focused on intense heatwaves (≥95th percentile) (Anderson and Bell, 2011; Zeng et al., 2014), although a greater proportion of deaths was attributable to moderate heat than extreme heat in Australia, China, Japan, South Korea, Sweden, UK, and the US (Gasparrini et al., 2015). Chen et al. found that the effect of mild heatwaves (90th percentile) on total mortality increased with the increase of heatwave duration, but the mortality due to ischemic heart disease was greater in two-day-duration heatwaves than



Emergency department attendances

Hospitalizations

Ambulance service uses

Emergency department attendances (hc)

Hospitalizations (hc)

Fig. 2. Generalized cross validation (GCV) scores for different temperature indicators.

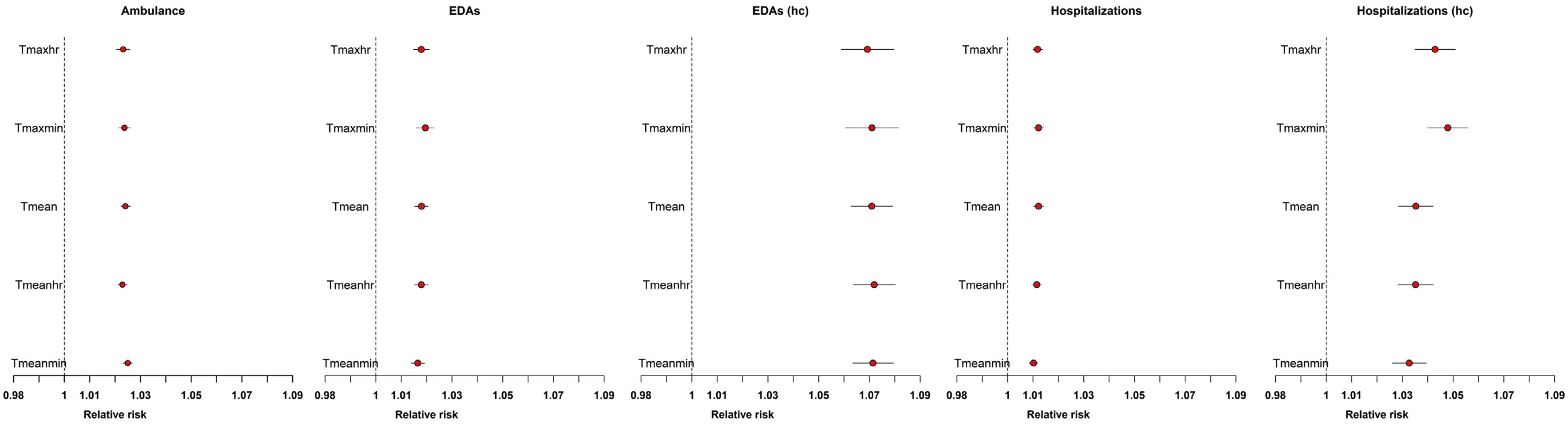


Fig. 3. Heatwave and five health events under different temperature indicators.

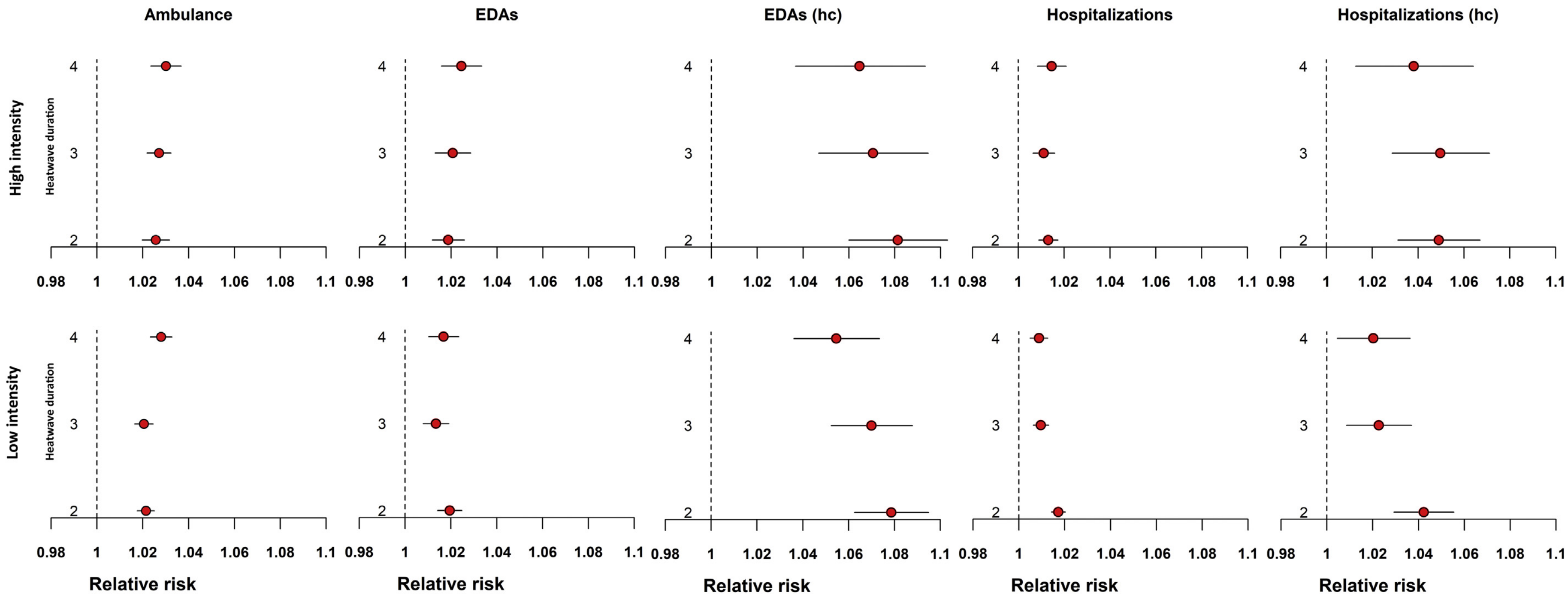


Fig. 4. Heatwave and five health events under different heatwave durations (Tmean).

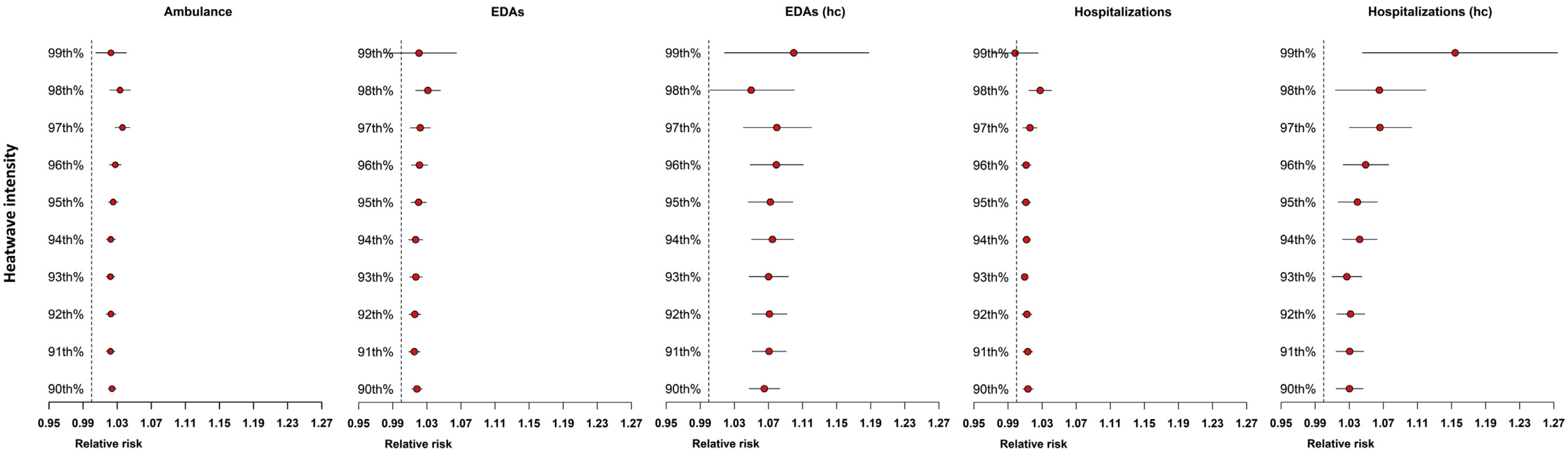


Fig. 5. Heatwave and five health events under different heatwave intensities (Tmean).

Table 4
Meta-regression results for heatwave effects on five health endpoints across different heatwave durations and intensities (Tmean).

	Ambulance service uses	EDA	EDA (hc)	Hospitalizations	Hospitalizations (hc)
Duration (low intensity*)	$P < 0.05$ (4 days vs 2 or 3 days)	$P > 0.05$	$P > 0.05$	$P < 0.05$ (2 days vs 3 or 4 days)	$P < 0.05$ (2 days vs 3 or 4 days)
Duration (high intensity*)	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$
Intensity (97th%)	$P < 0.05$ (90 vs 97)	$P > 0.05$	$P > 0.05$	$P > 0.05$	$P > 0.05$
Intensity (98th%)	$P < 0.05$ (90 vs 97)	$P > 0.05$	$P > 0.05$	$P < 0.05$ (90 vs 98)	$P > 0.05$
Intensity (99th%)	$P < 0.05$ (90 vs 97)	$P > 0.05$	$P > 0.05$	$P < 0.05$ (90 vs 98)	$P < 0.05$ (90 vs 99)

four-day-duration heatwaves (Chen et al., 2015). In our prior work, we observed that, in Brisbane, mortality increased consistently with the increase of heatwave duration, but the increase in emergency hospital admissions was the greatest during two-day-duration heatwaves when heatwave intensity was not high (90th percentile) (Tong et al., 2014). We speculate that mild (e.g., 90th to 93th percentiles) and short-lasting heatwaves may trigger pre-existing health conditions of Brisbane residents and people may quickly seek medical help once they feel uncomfortable. This finding implied that health and other government sectors need to be well prepared even in the face of short-lasting and mild heatwaves.

We have observed that 97th percentile appeared to be the temperature trigger where ASUs, hospitalizations, and hospitalizations (hc) increased sharply, which is consistent with a previous study looking at how heatwave effect on mortality changed with heatwave intensity in four communities of Guangdong, China (Zeng et al., 2014). Our prior work on heatwaves and mortality has also identified the same 97th percentile threshold (Tong et al., 2015), suggesting that setting 97th percentile as the heatwave early warning trigger point would be an ideal option to protect Brisbane residents from the adverse impact of heatwaves. Although our prior work has shown that heatwave effect on mortality rose alarmingly when heatwave intensity increased to 99th percentile (i.e., extreme heatwaves) (Tong et al., 2015), we found that the magnitude of heatwave effects on ASUs and hospitalizations became unstable (increasing or declining) when heatwave intensity increased from 97th percentile to 98th or 99th percentile (Fig. 5 and Figs. S3a–S3d). This unstable pattern can partially be attributable to the small number of extreme heatwave days (Son et al., 2012). Hajat et al. have found that heatwave effect on mortality consistently increased in three big European cities (Hajat et al., 2006) when heatwave intensity increased, but there is evidence on dropped heatwave effects on mortality in Asian countries when heatwave intensity increased from 97th or 98th percentile to 99th percentile (Chen et al., 2015; Son et al., 2012). The study of Anderson et al. in 43 communities, the US, has also observed big between-community heterogeneity in the modification effect of heatwave intensity on the association between heatwave and mortality (Anderson and Bell, 2011), and explained that this may be caused by different physical acclimatization of residents, different levels of exposure, different community-level adaptive capacities, and different demographics across different communities.

Heat-related mortality and morbidity (e.g., heat stroke) are just the top of the pyramid of health issues caused by heatwaves (Petitti et al., 2016). As expected, we found that the magnitudes of heatwave effects on EDAs (hc) and hospitalizations (hc) were much greater than heatwave effects on ASUs, EDAs and hospitalizations, calling for programs to remind health professionals and care providers about the possible increases of these heatwave related health consequences during heatwave days, given the fact that the knowledge on heat-related illnesses is still not abundant in some health professionals in Australia (Ibrahim et al., 2012). ASUs were found more sensitive to heatwaves than EDAs and hospitalizations in this study, implying that sufficient health resources may need to be allocated to ambulance service sector to tackle the adverse impacts of heatwaves in the future.

This study has several strengths. First, this is the first study assessing whether temperature observation time and type affected the impact of heatwaves on morbidity. Second, we adopted 29 heatwave definitions incorporating a wide range of heatwave durations and intensities to look at the impact of heatwaves on morbidity, and we also meta-analyzed the results, allowing us to investigate how heatwave duration and intensity influenced the impact of heatwaves on morbidity. Third, five health events, including possible health consequences of heat and/or dehydration, were used to examine whether heatwaves impacted various health events differently, and to make sure that the findings on temperature indicators, heatwave durations and intensities were robust across different health endpoints.

Two major limitations should also be acknowledged. First, this is a one-city study, and Brisbane has subtropical climate, and thus the generalization of our findings to other cities needs to be done with caution. Second, due to data availability issue, we were not able to obtain data on all health events covering the same period of time.

5. Conclusions

This study demonstrates that mean temperature was slightly better than maximum temperature to predict heatwave-related morbidity, and it is appropriate to calculate mean temperature by averaging daily maximum temperature and daily minimum temperature. Short-lasting and mild heatwaves were quite detrimental to health and we argued that the national heatwave definition of Australia which is “three or more days of unusually high maximum and minimum temperatures in any area” might not be optimal for Brisbane. When temperature reaches 97th percentile in the future, heat early warning system can be triggered, and the demand for ambulance service and health care may increase considerably during heatwave periods. Health and other relevant government sectors need to better prepare for increasing impact of heatwaves as climate change proceeds.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.02.268.

Conflict of interest

All authors declared that they have no any actual or potential conflict of interest.

Submission declaration and verification

This study has not been published previously. It is not under consideration for publication elsewhere, and its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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