Heatwave and infants' hospital admissions under different heatwave definitions

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Abstract

Objectives: Data on the health impacts of heatwaves in infants are limited, and this study aimed to examine how heatwaves affect hospital admissions in infants.

Methods: A quasi-Poisson generalized additive model was used to assess the effects of heatwaves on hospital admissions in infants from 1st January 2005 to 31st December 2015 in Brisbane, Australia, using a series of heatwave definitions after controlling for possible confounders. A case-only analysis was conducted to examine the possible modification effects of personal and community characteristics on the heatwaves effects on infants' hospital admissions.

Results: There was no significant increase in infants' hospital admissions when heatwave intensity was defined as mean temperature $\geq 90^{th}$ percentile or $\geq 95^{th}$ percentile of the mean temperature across the study period. When heatwave intensity increased to $\geq 97^{th}$ percentile, infants' hospital admissions increased significantly (RR: 1.05, 95% CI: 1.01, 1.10), and this increase raised with the increase of heatwave duration. No modification effect of gender, indigenous status, or Socio-Economic Indexes for Areas (SEIFA) level on heatwave effect was observed.

Conclusions: Infants in Brisbane were sensitive to intense heatwaves, and future heat early warning system based on a local evidence-based heatwave definition is needed to protect infants from heatwave impacts. Community-based heatwave adaptation programs aiming at raising the awareness of the adverse health impacts of intense heatwaves among infants' caregivers may relieve the postnatal health care demand in infants.

Keywords: Heatwave definition; infants; SEIFA

Major findings: Intense heatwaves increased infants' hospital admissions, and personal or community characteristics did not modify this effect.

1. Introduction

Heatwave is the most hazardous natural disaster in Australia (Coates, 1996). As projected, heatwaves will be more intense and frequent, and longer-lasting, in the future (Cowan and Purich, 2014). Infants are particularly vulnerable to the adverse health impacts of heatwaves owing to their less-developed thermoregulation and immune systems, and poor self-care capability (Xu et al., 2014b). Basagana et al. have observed significant effects of heatwaves on total and cause-specific mortality in infants in Catalonia region of Spain from 1983 to 2006 (Basagaña et al., 2011), and Auger et al. have found a significant impacts of high temperature on sudden infant deaths in Montreal, Canada, from 1981 to 2010 (Auger et al., 2015). Prior studies have observed the significant effects of heat/heatwaves on mortality in infants, but there is a dearth of literature on how heatwaves affect morbidity in infants (e.g., hospital admissions and emergency department attendances, etc.).

Previous studies have tended to use one or two heatwave definitions to quantify the health effect of heatwaves without providing convincing reasons behind their choices (Xu et al., 2016). Our prior work has demonstrated that a slight change in the heatwave definition may result in an appreciable difference in the heatwave-health relationship (Tong et al., 2010), and we have also observed that the magnitude of mortality increase may rise with the increases of heatwave intensity and duration (Tong et al., 2015). This suggests that the research community needs to develop a regionally/locally appropriate heatwave definition incorporating a proper heatwave intensity and duration to facilitate the development of heat early warning systems. Nevertheless, Sugg et al. have found that heat-related illness in North Carolina increased in abnormally high temperatures (e.g., 31 to 38 °C) but decreased in extremely high temperatures (e.g., above 38 °C), possibly due to people's adaptive actions in

extremely hot days (Sugg et al., 2016). Evidence of infant morbidity under certain heatwave conditions could further inform their care-givers to protect them in hot days.

A population's vulnerability to heat is mainly determined by three factors: exposure, sensitivity, and adaptive ability. The proposed ways to protect people from the adverse health impacts of heat are thus reducing the heat exposure and managing the related health risks (Huang et al., 2013). Some personal and community characteristics may modify the heat-health relationship (Benmarhnia et al., 2015), and researchers tend to do analyses stratified by these personal or community characteristics to identify the possible vulnerable groups, which may cause contrasting results as it largely depends on the measures used (e.g., percent change of mortality or morbidity when temperature is above certain threshold, or risk of one temperature percentile relative to another temperature percentile) (Benmarhnia and Kaufman, 2017). Case-only design can properly solve this issue as it does not rely on the measures but only focuses on the characteristics of all cases (Armstrong, 2003; Schwartz, 2005).

Heatwaves have been associated with increases in mortality and morbidity in Australia (Tong et al., 2012; Tong et al., 2014b), and elderly people (Tong et al., 2014b) and outside workers (Xiang et al., 2014) in Australia are particularly vulnerable to the adverse impacts of heatwaves. Children have also been reported as a group sensitive to heatwaves (Wang et al., 2014; Xu et al., 2014a), although no study, to the best of our knowledge, has looked at the relationship between heatwaves and infants' morbidity in Australia so far. The present time-series study quantified the effects of heatwaves on infants' hospital admissions in Brisbane, Australia, under different heatwave definitions, and assessed whether infants' personal or community characteristics modified the heatwave effects using a case-only design.

2. Methods

2.1 Data collection

Brisbane, the capital city of Queensland, is located on the east coast of Australia. It has a typical sub-tropical climate. The daily data on hospital admissions in children under one year of age (i.e., infants) from 1st January 2005 to 31st December 2015 in Brisbane, Australia, were obtained from Queensland Health, and the data were originally supplied by 11 hospitals including Caboolture Hospital, Ipswich Hospital, Logan Hospital, Mater Children's Public Hospital, Princess Alexandra Hospital, Queen Elizabeth II Jubilee Hospital, Redcliffe Hospital, Redland Hospital, Royal Brisbane and Women's Hospital, Royal Children's Hospital and the Prince Charles Hospital. The data on infants' hospital admissions included the information on gender and indigenous status. Data on Socio-Economic Indexes for Areas (SEIFA) (the community level characteristic in this study) were obtained from Australian Bureau of Statistics (ABS) (ABS, 2012). Daily data on climatic factors, including maximum and minimum temperatures, and relative humidity were supplied by Australian Bureau of Meteorology. The climatic data were collected from two monitoring stations (i.e., Brisbane station, and Brisbane Aero station), and the average value of two stations were used. There were some missing years in the data collected from Brisbane Aero station, and for these years, we used only the data from Brisbane station. Our previous study has found that using one-station data or multiple-station data did not make much difference in assessing temperature and health relationship in Brisbane (Guo et al., 2013). Daily mean temperature was calculated by averaging daily maximum temperature and minimum temperature due to data availability issue. Our previous work has observed that mean temperature or other temperature indicators performed similarly (e.g., maximum or mean temperature) in assessing the effect of heat on mortality (Yu et al., 2011). Data on air pollutants for the same

time period, including daily average particulate matter ≤ 10μm (PM_{10}) (μg/m^3), and daily average nitrogen dioxide (NO_2) (μg/m^3) were obtained from the Queensland Department of Environment and Heritage Protection. The air pollution data were originally collected from two monitoring stations (i.e., Brisbane CBD station, and Brisbane Rocklea station), and the average values of air pollutions in these two stations were used. Ethical approval (approval number: 1500000369) was obtained from the Queensland University of Technology Human Research Ethics Committee prior to the data collection.

2.2 Heatwave definitions

Our previous work has investigated how temperature definition (i.e., duration and intensity) may affect the estimation of heatwave effects on morbidity and mortality, and thus we combined duration (2, 3 or 4 days) and intensity (90th percentile, 95th percentile, or 97th percentile) to define heatwave (Tong et al., 2010). We chose these durations (i.e., 2, 3 or 4 days) because they are the most commonly used durations in heatwave definitions used in prior literature (Xu et al., 2016), and we chose these intensities partially based on our prior work (Tong et al., 2014a) and partially because these intensities can offer a valid comparison because they are not too close. Mean temperature was used as the temperature indicator for heatwave definition (Tong et al., 2015). For example, the 1st heatwave definition was: Mean temperatures ≥ 90th percentile of the whole year temperature distribution for ≥ 2 days. The reasons that we chose the whole year data rather than summer season are: 1). Brisbane is a subtropical city and hot days sometimes occur beyond summer season; and 2). this study aimed to look at whether mild heatwave and intense heatwave affected infants differently. In total, there were nine heatwave definitions (Table 1).

2.3 Data analysis

A Poisson generalized additive model (GAM) allowing for over-dispersion was used to quantify the effects of heatwaves on infants' hospital admissions (Peng et al., 2017). A distributed lag non-linear model (DLNM) was used to capture the possible lagged effect of heatwaves (Gasparrini, 2011). Possible confounders, including PM_{10}, NO_2, relative humidity, seasonal and long-term trends, were controlled for in the model. Specifically, we used a spline with seven degrees of freedom (*df*s) each year to control for seasonal and long-term trends, and the choice of *df*s was based on the minimum generalized cross validation (GCV) (Wang et al., 2012). A case-only design was used to detect whether the personal and community characteristics modify the association between heatwave and infants' hospital admissions. Case-only design was originally used to examine the gene-environment interactions, and then it was introduced to look at how characters which do not change over time may modify the association between time-varying factors (e.g., temperature or air pollutants) and health outcomes. The details (e.g., rationale and implementation, etc.) can be found in previous papers (Madrigano et al., 2015; Zanobetti et al., 2013). The personal characteristics in this study were gender and indigenous status, and the community characteristics included SEIFA. SEIFA is a continuous variable and it is used to rank areas according to socio-economic advantage and disadvantage (e.g., wealth, occupation, and education) based on census data in Australia. Data on SEIFA were linked to hospitalization data according to the postcode of the infant's residence. For the case-only study, we categorized SEIFA into a three-category variable according to its 33th percentile and 66th percentile.

We did sensitivity analyses to ensure the results are robust. Specifically, we changed the *df*s for the nonlinear time trend from seven to ten in the time series analysis, and controlled for PM_{10} and NO_2 in the case-only analysis. Further, in the case-only analysis, we also included an annual sine-cosine pair to control for a seasonal component that may confound the

modifier of interest and heatwaves. The time-series analyses were conducted in R package (version 3.2.2) with "mgcv" and "dlnm" to conduct GAM and DLNM (Gasparrini et al., 2010). The case-only analysis was conducted in SPSS (SPSS 23, IBM Corp., Armonk, NY, USA) (Qiu et al., 2016).

3. Results

There were 53, 792 infants who were hospitalized from 2005 to 2015. Table 2 presents the summary statistics of climatic variables, air pollutants, and hospital admissions in Brisbane, Australia, from 2005 to 2015. The mean values for mean temperature, relative humidity, PM_{10}, and NO_2 were 20.6 °C, 71.9%, 15.3 μg/m^3 and 7.9 μg/m^3, respectively. The daily mean value for infants' hospital admissions was 13.4. There were more boys (7.7), more children with the indigenous status as "neither aboriginal nor Torres Strait Islander origin" (12.7), and more children from low SEIFA suburbs (6.0), compared with their counterparts.

Figure 1 illustrates the temporal distribution of daily hospital admissions in infants. The four panels (from top to bottom) show the original time-series distribution, the seasonal trend, the long-term trend, and the residuals (i.e., those which cannot be explained by seasonal trend or long-term trend), respectively. It can be seen from the 3rd panel (i.e., the long-term trend panel) that the daily number of hospital admissions in infants increased from approximately 8 to 20. This figure suggests that there was a long-term increasing trend in daily hospital admissions in infants in Brisbane.

Figure 2 shows the effects of heatwaves on infants' hospital admissions under different heatwave definitions, demonstrating that when mean temperature was ≥ 97th percentile of the whole period's mean temperature for 2 days or more, infants' hospital admissions increased significantly, and this increase was greater when the heatwave period lasted longer.

Table 3 is the result of the case-only study. In this table, every character has a reference group (i.e., girls, children who were neither aboriginal nor Torres Strait Islander origin, and children from high SEIFA group), and the other counterpart groups were compared with this reference group, and RR>1 (95% confidence interval does not cover 1) indicates a higher vulnerability to heatwaves. Table 3 reveal that there was no modification effect of gender, indigenous status, or SEIFA on heatwave impacts on infants' hospital admissions.

Figure 3 (supplementary material) shows the sensitivity analysis results after changing the *df*s for seasonality and long-term trend. Specifically, Figures 3a, 3b, and 3c present the results for *df*s=8, *df*s=9, and *df*s=10, respectively. Table 4 (supplementary material) shows the sensitivity analysis results for the case-only study. Specifically, Table 4a presents the result for controlling for PM_{10} and NO_2, and Table 4b presents the result for including an annual sine-cosine pair to control for a seasonal component. These results suggest that the main results are robust.

4. Discussion

This study has observed an appreciable increase in the number of infants' hospital admissions in Brisbane from 2005 to 2015, and has found significant effects of heatwaves on infants' hospital admissions when the mean temperature was ≥ 97^{th} percentile for ≥ 2 days, and this impact was greater when the heatwave period lasted longer. There was no modification effect of gender, indigenous status or SEIFA on the relationship between heatwave and infants' hospital admissions.

Queensland population increased by 13% from 2005 to 2010, and increased by 7% from 2011 to 2015 (ABS, 2007, 2016). During the 11-year study period, children aged 0-14 years represented approximately 20% of Queensland's population from 2006 to 2015, and the situation was similar in Brisbane (ABS, 2007, 2016), suggesting that the population of

children may increase by roughly 10% during our study period. By contrast, the number of infants' hospitalizations had a more-than-two-fold increase, indicating that the health service demand per person in children of Brisbane increased considerably. The reason behind this finding may be multifaceted (e.g., better access to health care, more infants' morbidity, or increased chronic disease (e.g., obesity) during pregnancy, etc.), and further studies exploring the drivers of this increasing health service demand are warranted as it can facilitate the development of tailored health care policies in Brisbane.

In this study, we did not find any significant effects of heatwaves on infants' hospital admissions when the temperature intensity was ≥ 90^{th} percentile or ≥ 95^{th} percentile, but found that infants' hospital admissions increased significantly when mean temperature was ≥ 97^{th} percentile of the whole period's mean temperature for ≥ 2 days, with the relative risk rising from 1.05 (95% CI: 1.01, 1.10) to 1.18 (95% CI: 1.05, 1.32) when the duration of heatwave changed from 2 days to 4 days. In future work we will use Bayesian hierarchical model with segment-spline (i.e., 90^{th}, 90.5^{th}, …, 99^{th}) to identify the temperature intensity threshold in more detail and to examine whether the trend across heatwave intensities and durations is consistent (Tong et al., 2015). Although we observed that the magnitude of the association (i.e., RR) between heatwave and infants' hospital admissions increased as the duration changed from 2 to 4 days, we also acknowledged that each increasing duration category is also a subset of the former. A study conducted in Huainan, China, has found that the fraction of emergency ambulance dispatches (i.e., AR) attributable to mild heatwaves (e.g., 95^{th} percentile & 2 days) was greater than the fraction attributable to intense heatwaves (e.g., 99^{th} percentile & 3 days).

So far, data on the relation between heatwave and infants' health are scarce (Xu et al., 2014b), and the present study, to the best of our knowledge, is the first study specifically looking at the impacts of heatwaves on infants' hospital admissions. Basagana et al. have

observed the effects of heatwaves on infants' cause-specific mortality in the Catalonia region of Spain, and they reported that these heatwave-related deaths were mainly due to those diseases originated in the perinatal period (Basagaña et al., 2011). Because of infants' underdeveloped thermoregulation and immune systems as well as their very low self-care ability, they may be more sensitive to heatwaves and their pre-existing health conditions originated in the perinatal period if outdoor temperature is extremely high. Given the increased hospitalizations in infants during intense heatwaves, parents should be reminded about the possible adverse health impacts of heatwaves on their children.

Understanding and publicizing vulnerability to heatwave-related morbidity is an essential step to orient tailored heatwave adaptive actions toward sensitive groups. We did not find any modification effect of gender, indigenous status, or SEIFA on the relationship between heatwaves and infants' hospital admissions. Benmarhnia et al. systematically reviewed the groups particularly vulnerable to heat-related mortality and found individual-level socioeconomic factors rather than neighborhood socioeconomic factors modified the effect of heat on mortality (Benmarhnia et al., 2015). Whether infants' indigenous status or SEIFA level modifies the health effects of heatwaves may not truly reflect the advantage/disadvantage of these factors in protecting them in heatwaves, but rather indicating how these factors modify their care-givers' protection behaviors upon them during heatwave days. The negative modification effect results we observed suggest that, in Brisbane, infants of different indigenous statuses and from suburbs of different socioeconomic statuses were all vulnerable to the health impacts of heatwaves.

This study has two major strengths. First, we used a series of heatwave definitions, allowing us to possibly identify a temperature triggering point for protecting infants from heatwave effects in the future. Second, we specifically focused on infants, a group which has very low self-care capacity in the face of heatwaves, and the modification effect analysis we did may

give some clues to the future allocation of heatwave prevention resources. Three weaknesses should also be acknowledged. First, the data availability issue restricted us from exploring the modification effects of more community characteristics (e.g., air conditioning use rate, etc.). Second, the way of calculating mean temperature may affect the estimation of the association between heatwave and hospitalization, and due to data availability issue, we simply calculated mean temperature by averaging maximum temperature and minimum temperature. This issue will be resolved by collecting temperature values measured at different time points across a whole day in our future work. Third, this is a one-city study, and the generalization of our findings to regions of different climates should be done with caution.

Infants' hospital admissions increased during heatwaves with certain intensity, and infants of different genders, indigenous statuses, or SEIFA levels did not differ in terms of their vulnerability to heatwaves. Future tailored heat early warning and community-based heatwave adaptation programs' emphasis on educating the care-givers of infants may help relieve the health service demand in infants during heatwave periods, although better understanding of additional underlying mechanisms and current caregiver behaviour are essential before public health teams barrel in with possibly misguided solutions.

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Figure 1. Temporal distribution of infants' hospitalizations in Brisbane, Australia

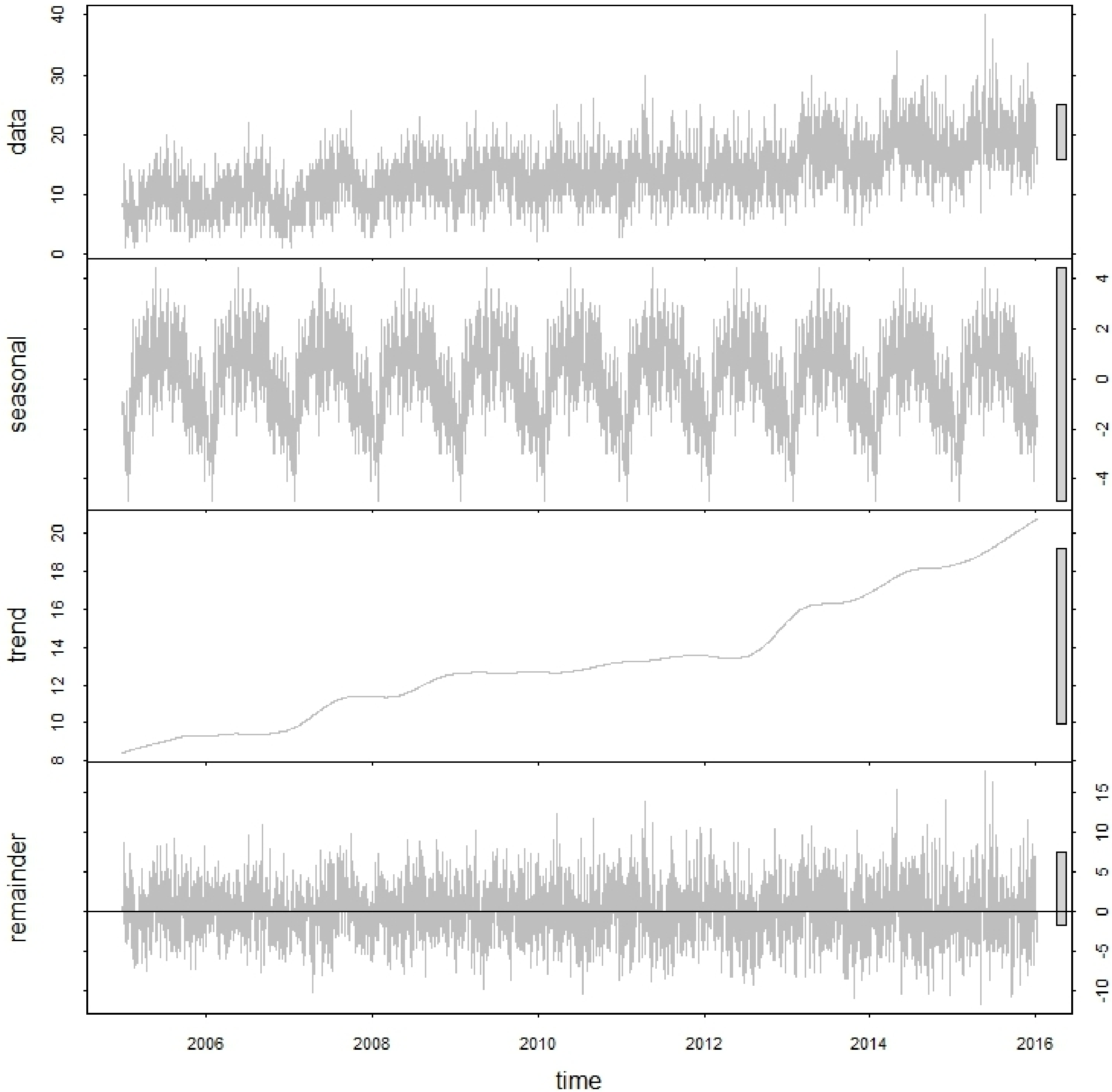

Figure 2. Heatwave and infants' hospital admissions under nine definitions

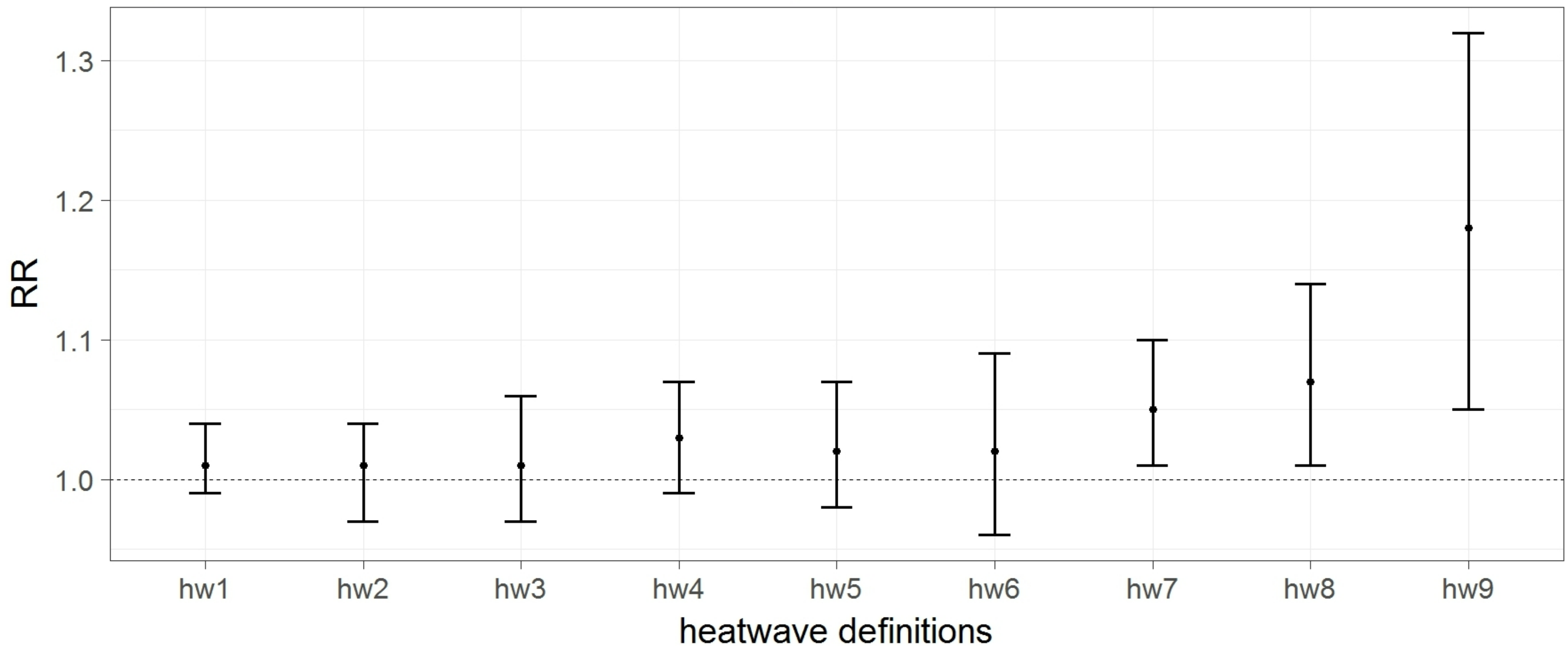

Figure 3. Heatwave and infants' hospital admissions (*df*s = 8, 9 or 10)

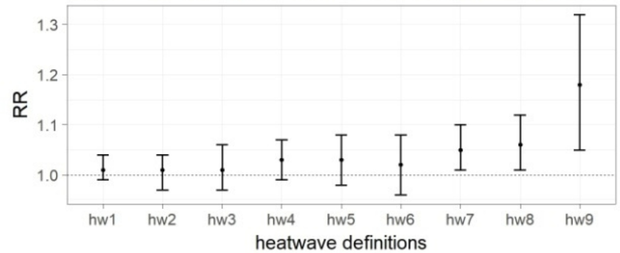

Figure 3a. Heatwave and infants' hospital admissions

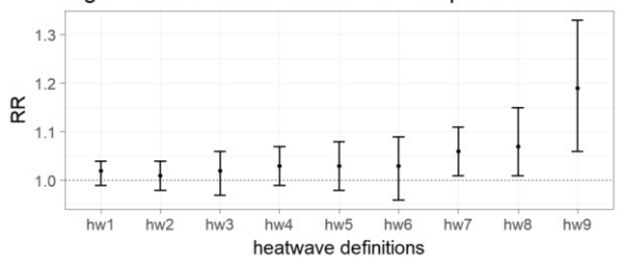

Figure 3b. Heatwave and infants' hospital admissions

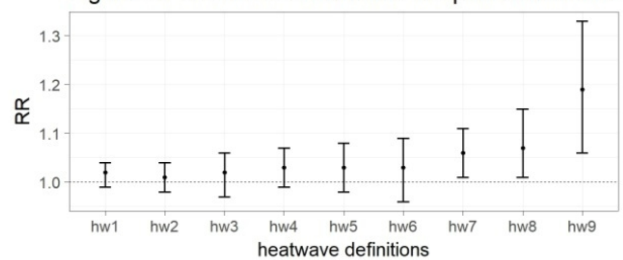

Figure 3c. Heatwave and infants' hospital admissions

Table 1. Heatwave definitions used in this study

Heatwave types	Specific definitions
hw1	90^{th} percentile & 2 days
hw2	90^{th} percentile & 3 days
hw3	90^{th} percentile & 4 days
hw4	95^{th} percentile & 2 days
hw5	95^{th} percentile & 3 days
hw6	95^{th} percentile & 4 days
hw7	97^{th} percentile & 2 days
hw8	97^{th} percentile & 3 days
hw9	97^{th} percentile & 4 days

Table 2. The summary statistics of climatic factors, air pollutants and infants' hospital admissions (HAs) from 2005 to 2015 in Brisbane, Australia

	Range	Mean	Percentile	
			25	75
Mean temperature (°C)	9.0 – 30.9	20.6	17.3	23.9
Relative humidity (%)	14.8 – 96.4	71.9	66.3	78.9
PM_{10} (μg/m^3)	2.5 – 960.0	15.3	11.1	17.4
NO_2 (μg/m^3)	0.1 – 29.7	7.9	4.0	10.8
Total HAs	1.0 – 40.0	13.4	10.0	17.0
HAs in boys	0 – 23.0	7.7	5.0	10.0
HAs in girls	0 – 20.0	5.7	4.0	7.0
HAs in aboriginal but not Torres Strait Islander origin	0 – 6.0	0.6	0	1.0
HAs in Torres Strait Islander origin	0 – 2.0	0.1	0	0
HAs in both aboriginal and Torres Strait Islander origin	0 – 2.0	0.1	0	0
HAs in neither aboriginal nor Torres Strait Islander origin	1.0 – 39.0	12.7	9.0	16.0
HAs in high SEIFA population	0 – 13.0	3.2	2.0	4.0
HAs in middle SEIFA population	0 – 15.0	4.2	2.0	6.0
HAs in low SEIFA population	0 – 22.0	6.0	4.0	8.0

Table 3. Modification by personal and community characteristics of heatwave impacts on infants' hospitalizations

	Heatwave definitions		
	97^{th} percentile & 2 days	97^{th} percentile & 3 days	97^{th} percentile & 4 days
Girls	1	1	1
Boys	1.05 (0.92,1.19)	1.02 (0.87,1.20)	0.97 (0.78,1.20)
Neither aboriginal nor Torres Strait Islander origin	1	1	1
Aboriginal but not Torres Strait Islander origin	1.02 (0.74,1.41)	1.08 (0.73,1.60)	1.11 (0.71,1.70)
Torres Strait Islander origin	0.94 (0.30,3.00)	0.99 (0.24,4.04)	0.98 (0.45,2.65)
Both aboriginal and Torres Strait Islander origin	1.43 (0.53,3.89)	1.72 (0.54,5.46)	1.56 (0.58,4.98)
High SEIFA	1	1	1
Middle SEIFA	0.97 (0.81,1.16)	1.00 (0.80,1.25)	0.85 (0.64,1.13)
Low SEIFA	1.03 (0.88,1.22)	1.03 (0.84,1.26)	0.93 (0.71,1.20)

Table 4a. Modification by personal and community characteristics of heatwave impacts on infants' hospitalizations (controlling for PM_{10} and NO_2 in the case-only study)

	Heatwave definitions		
	97th percentile & 2 days	97th percentile & 3 days	97th percentile & 4 days
Girls	1	1	1
Boys	1.06 (0.92,1.20)	1.02 (0.87,1.20)	0.98 (0.76,1.24)
Neither aboriginal nor Torres Strait Islander origin	1	1	1
Aboriginal but not Torres Strait Islander origin	1.02 (0.74,1.41)	1.09 (0.74,1.62)	1.11 (0.71,1.70)
Torres Strait Islander origin	0.94 (0.30,3.00)	0.99 (0.24,4.04)	0.99 (0.46,2.67)
Both aboriginal and Torres Strait Islander origin	1.44 (0.50,3.93)	1.72 (0.54,5.46)	1.56 (0.58,4.98)
High SEIFA	1	1	1
Middle SEIFA	0.97 (0.81,1.16)	1.01 (0.80,1.27)	0.85 (0.64,1.13)
Low SEIFA	1.03 (0.88,1.22)	1.03 (0.84,1.26)	0.94 (0.72,1.23)

Table 4b. Modification by personal and community characteristics of heatwave impacts on infants' hospitalizations (including a seasonal component in the case-only study)

	Heatwave definitions		
	97th percentile & 2 days	97th percentile & 3 days	97th percentile & 4 days
Girls	1	1	1
Boys	1.05 (0.92,1.19)	1.01 (0.85,1.18)	0.97 (0.78,1.20)
Neither aboriginal nor Torres Strait Islander origin	1	1	1
Aboriginal but not Torres Strait Islander origin	1.02 (0.73,1.42)	1.08 (0.73,1.60)	1.11 (0.71,1.70)
Torres Strait Islander origin	0.94 (0.30,3.00)	0.98 (0.25,4.06)	0.98 (0.45,2.65)
Both aboriginal and Torres Strait Islander origin	1.45 (0.58,3.94)	1.72 (0.54,5.46)	1.56 (0.58,4.98)
High SEIFA	1	1	1
Middle SEIFA	0.97 (0.81,1.16)	0.99 (0.78,1.21)	0.85 (0.64,1.13)
Low SEIFA	1.02 (0.86,1.24)	1.03 (0.84,1.26)	0.93 (0.71,1.20)