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Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index

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Abstract:

Purpose: Heatwaves, or extended periods of extreme heat, are predicted to increase in frequency, intensity and duration with climate change, but their impact on occupational injury has not been extensively studied. We examined the relationship between heatwaves of varying severity and work-related injuries and illnesses. We used a newly proposed metric of heatwave severity, the Excess Heat Factor (EHF), which accounts for local climate characteristics and acclimatization and compared it with heatwaves defined by daily maximum temperature.

Methods: Work-related injuries and illnesses were identified from two administrative data sources: workers' compensation claims and work-related ambulance call-outs for the years 2003-2013 in Adelaide, Australia. The EHF metrics were obtained from the Australian Bureau of Meteorology. A time-stratified case-crossover regression model was used to examine associations between heatwaves of three levels of severity, and: workers compensation claims; and work-related ambulance call-outs.

Results: There was an increase in work-related ambulance callouts and compensation claims during low and moderate severity heatwaves as defined using the EHF, and a non-significant decline during high severity heatwaves. Positive associations were observed during moderate heatwaves in compensation claims made by new workers (RR 1.31, 95%CI: 1.10-1.55), workers in medium-sized enterprises (RR 1.15, 95%CI: 1.01-1.30), indoor industries (RR 1.09, 95%CI: 1.01-1.17), males (RR 1.13, 95%CI: 1.03-1.23) and labourers (RR 1.21, 95%CI: 1.04-1.39).

Conclusions: Workers should adopt appropriate precautions during moderately severe heatwaves, when the risks of work-related injuries and illnesses are increased. Workplace policies and guidelines need to consider the health and safety of workers during heatwaves with relevant prevention and adaptation measures.

Keywords: Workers' compensation claims; Case-crossover design; Heatwaves; Occupational Health; Worker safety

1. Introduction

The detrimental effect of temperature upon human health assessed in terms of increased mortality and morbidity is well established (Song et al. 2017). Major heatwaves (extended periods of unusually high temperatures) have been associated with an increased health burden in populations over recent years. For example, heatwaves in Australia in 2009 (Nitschke et al. 2011; Zhang et al. 2013; Zhang et al. 2016) and Europe in 2003 (Le Tertre et al. 2006) have drawn increasing interest among researchers, governments and policy makers. The majority of health research has predominantly focussed on the general population, while the occupational health effects have been largely overlooked despite their potential economic costs and impact on quality of life.

The direct effects of extreme heat on workers' health was evident during the 2003 heatwave in France where a considerable number of deaths occurred in those of working age (15-64 years). This age group has also been found to be at risk in Australia where a 37% increase in mortality was reported during a record-breaking 2009 severe heatwave in Adelaide, South Australia (Nitschke et al. 2011). Apart from elevating the risk of symptoms leading to heat-related illness (HRI) and in severe cases, death, there is increasing evidence that high ambient temperatures could increase the risk of occupational injuries (Adam-Poupart et al. 2015; Fogleman et al. 2005; McInnes et al. 2017a; McInnes et al. 2017b; Morabito et al. 2006; Spector et al. 2016; Tawatsupa et al. 2013; Xiang et al. 2014c). The occurrence of work-related accidents during high temperatures may be attributed to multiple factors that can compromise workplace safety, including physical discomfort, decreasing psychomotor performance, fatigue and reduced alertness arising from heat exposure (Kjellstrom et al. 2016; Ramsey 1995; Xiang et al. 2014a). Consecutive days of very high temperatures can have significant health impacts on workers with physical fatigue carrying over into the following days, thus increasing the risk of injuries.

To the authors' knowledge, only three Australian studies have investigated the impact of sustained high ambient temperatures on workers' health and safety (McInnes et al. 2017b; Rameezdeen and Elmualim 2017; Xiang et al. 2014b). Two studies (Rameezdeen and Elmualim 2017; Xiang et al. 2014b) did not find any statistically significant difference in overall injury claims between heatwave and non-heatwave periods, although a 6.2% increase in claims was observed for outdoor industries (Xiang et al. 2014b). An increased risk of injury was observed in Melbourne, Australia during two and three consecutive days of hot (but not extreme) weather, with a 15% increased injury risk when the daily maximum temperature was above 33^{o}C (McInnes et al. 2017b). Given that the frequency, duration, and intensity of heatwaves are predicted to increase in the future due to climate change (IPCC 2014), it is imperative to better understand how heatwaves might affect workers directly or indirectly in order to inform public health policies that can help minimise the risks.

One of the key challenges presented for heatwave studies relates to heatwave definitions, as currently there exists no standardized definition (Guo et al. 2017; Nairn and Fawcett 2014; Xu et al. 2016). Most studies (Anderson and Bell 2011; Kent et al. 2014; Ma et al. 2015) have defined heatwaves utilising a combination of duration (≥ 2, ≥ 3, or ≥ 4days) and intensity (95th or 97.5th percentiles of temperature). Different temperature metrics have been used (e.g. minimum/mean/maximum temperature or apparent temperature, Humidex and Heat Index), while some studies have used extended definitions exploring characteristics such as early or late season heatwaves (Gronlund et al. 2014; Khalaj et al. 2010; Mastrangelo et al. 2007). As a result, it is difficult to make consistent statements on both the current and future health impacts using these different definitions.

In this context, the Australian Bureau of Meteorology (BOM) recently introduced a map-based heatwave forecasting service using the Excess Heat Factor (EHF) metric based on average daily temperatures (Nairn and Fawcett 2014). Recent studies that have used the EHF as an exposure metric in the assessment of health impacts have found it to be a useful heatwave indicator (Hatvani-Kovacs et al. 2016; Jegasothy et al. 2017; Scalley et al. 2015; Williams et al. 2018; Xiao et al. 2017). The EHF is also becoming widely used internationally due to its applicability in both tropical and temperate regions, and as such is included in the World Health Organization (WHO) and World Meteorological Organization (WMO) guidance documents on warning systems (World Meterological Organization and World Health Organization 2015).

With the association between heatwaves and occupational injuries not well established, this study aimed to characterize the relationship between heatwaves of varying severity as defined using the EHF, and work-related injuries and illnesses in Adelaide, using two data sources:- workers' compensation claims data and ambulance data. We hypothesize that EHF-defined heatwaves are associated with an increased risk of work-related injuries and illnesses.

2. Materials and Methods

2.1 Study site

Adelaide, the capital city of the state of South Australia, is the fourth largest Australian city covering an urban area of 3,258 km² with a population of 1.6 million. The city has a temperate climate with mild winters and hot, dry summers.

2.2 Data sources:

2.2.1 Workers' compensation claims data

Compensation claims data for the period from 1st July 2003 to 30th June 2013 were aggregated by 'Return to Work SA', a government agency that manages the prevention and compensation of occupational accidents and diseases in South Australia. The dataset covered all reported and active claims in the Adelaide metropolitan area defined as the suburbs encompassing postcodes

5000-5200. The data included details on worker characteristics (age, gender, type of work, industry), injury and illness information (agency, mechanism, type and body location) and outcome details (hospitalisations, deaths, days lost from work and total expenditure). More details about this data are described elsewhere (Dumrak et al. 2013; Rameezdeen and Elmualim 2017; Xiang et al. 2014b; Xiang et al. 2014c). For the purposes of this study, we used all accepted compensation claims (comprising work-related injuries and illnesses) as the outcome variable in line with previous studies (Rameezdeen and Elmualim 2017; Xiang et al. 2014b).

2.2.2 Ambulance call-outs

Ambulance services in Adelaide are predominantly provided by the South Australian Ambulance Service (SAAS). Data pertaining to ambulance call-outs (excluding between hospital transfers) logged between 1st July 2003 and 30th June 2013 were examined. For the purposes of this study, we selected only SAAS callouts coded as 'work-related/industrial'.

2.2.3 Meteorological data

The BOM provided the climate data for the study period, including daily maximum and minimum temperatures (T_{max} °C, T_{min} °C) and relative humidity (RH %) from the Kent Town weather station (023090), considered to best represent the Adelaide metropolitan area (Hatvani-Kovacs et al. 2016; Milazzo et al. 2016; Nitschke et al. 2016; Xiang et al. 2014b; Xiang et al. 2014c).

2.3 Heatwave (HW) definitions

Heatwaves (HW) were defined using the EHF definition according to Nairn and Fawcett (Nairn and Fawcett 2014). EHF captures the HW intensity based on a three-day averaged daily mean temperature (T_{mean}) consisting of two components: the significance index and the acclimatization index. These are referred to as the Excess Heat Indices (EHIs) and are calculated as:

$$EHI_{sig} = (T_i + T_{i+1} + T_{i+2})/3 - T_{95} \qquad (1)$$

$$EHI_{accl} = (T_i + T_{i+1} + T_{i+2})/3 - (T_{i-1} + \ldots + T_{i-30})/30 \qquad (2)$$

The comparison of the three-day averaged T_{mean} to the 95th T_{mean} percentile and average T_{mean} over the previous 30days generates the above EHI's. The product of equations (1) and (2) gives EHF as:

$$EHF = EHI_{sig} \times \max(1, EHI_{accl}) \qquad (3)$$

Days with a positive EHF indicate the existence of heatwave conditions and the severity level of such events are expressed as an EHF severity index (EHF_{sev}) calculated as:

$$EHF_{sev} = EHF \div 85^{th} \text{ percentile of all positive values} \qquad (4)$$

Days when EHF_{sev} is between 0 and 1, and greater than 1, indicates heatwaves of 'low' and 'severe' intensity, respectively, whereas those greater than 3 are identified by the BOM as an 'extreme' heatwave (Nairn and Fawcett 2014). Thus, EHF is primarily based on the local climate and on daily temperature, and accounts for the significance of consecutive hot days and acclimatization. Other heatwave characteristics such as intensity, frequency and duration are represented, making EHF useful for forecasting heatwaves (Nairn and Fawcett 2014). Additionally, the effects of relative humidity that play a considerable role in human response to heat are also indirectly factored in the formula with the use of T_{mean}. Further details on EHI's and EHF (e.g. development, calculation, and usage) are described elsewhere (Nairn and Fawcett 2014).

The EHF and EHF severity data for the Kent Town monitoring station were supplied by the BOM as a gridded dataset using low resolution (0.25° X 0.25°, approximately 25Km x 20 Km) operational daily temperature analyses. Generally heatwave severity is classified as above by the BOM. However, as there were very few days of EHF_{sev} ≥3 during the study period, for our purposes extreme HW days were included within the high-severity category that we defined using a lower criterion (EHF_{sev} ≥2) as described below. Hence, we used the following EHF_{sev} categories (HWD1):

- No heatwave: daily EHF_{sev} ≤0
- Low-intensity: daily EHF_{sev} >0 and <1
- Moderate-severity: daily EHF_{sev} ≥1 and <2
- High-severity: daily EHF_{sev} ≥2

Additionally, we also used a definition (HWD2) using T_{max} of ≥3 consecutive days with daily T_{max} ≥35°C (as in previous studies) for comparison (Milazzo et al. 2016; Nitschke et al. 2016; Xiang et al. 2014b).

2. 4. Study design and analysis

A time-stratified case-crossover study design was used to assess the association between heatwave severity and the outcome variables of interest. In case-crossover design each ‘case’ serves as their own control and time-invariant confounders and seasonal patterns are controlled for (Maclure 1991). In this study, the ‘cases’ are accepted worker’s compensation claims or reported ‘work-related ambulance call-outs’. Heatwave exposure in the ‘case period’ was compared with the exposures during the ‘control period’ (other days within the strata when the case did not occur). A seven-day strata was utilized to adjust for week to week changes in worker numbers.

Risk periods were pre-defined heatwave days of varying severity and the referent period was all non-heatwave days. Key confounding factors taken into account include: seasonality, day of the week and public holidays. To control for seasonality we restricted the analysis to the warm-season (October-March) and adjusted for public holidays with three separate indicator binary variables (Christmas Day, New Year's Day and other public holidays). To model the well-known pattern in workers' activity during the week, the days of the week were modelled using an independent binary variable for each seven-day window except the reference day (Friday). We fitted the case-crossover design using a generalized linear model (GLM) assuming a Poisson distribution. Results are presented as risk ratios (RR) with 95% confidence intervals (CIs) for the number of daily compensation and work-related ambulance call-outs during heat wave periods of low-intensity, moderate and high severity, compared with non-heatwave periods in the warm-season. Additionally, stratified analysis by worker (age group, gender), work (industry, occupation) and work environment characteristics (work site location, size of business) was conducted to identify vulnerable subgroups. We also investigated lagged effects (days 1 and 2) of EHF_{sev} on total compensation claims and work-related ambulance call-outs. As we found no evidence of a marked lagged effect, these are not presented in the results section.

2.4.1 Cross-validation

The predictive ability of each HW definition was assessed using a 50-fold cross-validation. Details of this technique are given elsewhere (Han et al. 2012). The benefit of using this robust model selection technique is that more realistic predictions can be obtained for future studies with the inference being less tailored to the dataset in which this procedure is applied (Barnett et al. 2010). We randomly removed one day from the seven-day strata throughout the study period and then ran the GLM regression models 50 times. Standard errors were then created by comparing the actual number of claims to the predicted values with the smaller root mean square error indicating the better prediction of the model.

All analysis was carried out using the R statistical software version 3.2.3, with the 'season' package used to fit the CCO design (Barnett and Dobson 2010).

3. Results

3.1. Descriptive statistics

Within the Adelaide metropolitan region during the period of 1st July 2003- 30th June 2013, there were 224,631 (76.1%) accepted compensation claims of which 111,254 (49.5%) occurred during the warm-season (October-March). Males accounted for 66.4% of the claims and approximately two-thirds (69.5%) of claims were for people aged 25-54 years. On the other hand, there were 5,910 (0.6%) work-related ambulance call-outs out of a total of 931,786 ambulance call-outs during the same time frame of which half (2,987) occurred during the warm-season.

There were 118, 19 and 7 days defined using the EHF (HWD1) as low-intensity, moderate and high-severity heatwaves, respectively. The corresponding three-day mean T_{max} during these heatwave days were 35.1 °C, 38.2 °C and 41.1 °C. By contrast, using the T_{max} definition of heatwaves (HWD2), there were 106 heatwave days.

3.2. Association between heatwave and work-related injuries and illness

3.2.1 Total effects

There was an increase in compensation claims during low-intensity and moderate-severity heatwaves and a non-significant decline during the high-severity heatwaves (Figure 1a). The RR during moderate-severity heatwaves was 1.08 (95% CI: 1.01-1.17) for overall compensation claims and 1.10 (95% CI: 1.02-1.19) for injury claims. By contrast the RR for illness claims was 1.13 (95% CI: 1.03-1.25) during low-intensity heatwaves. However, based on HWD2, there were no statistically significant difference detected in claims between heatwave and non-heatwave periods.

A similar trend was observed for work-related ambulance callouts with an increase in call-outs during low-intensity and moderate-severity heatwaves and a decline during high-severity heatwaves (Figure 1b). The corresponding RR during moderate-severity heatwave was 1.21 (95% CI: 0.81-1.81) for work-related ambulance call-outs.

3.2.2. Effect estimates by workers' demographics, work and work environment characteristics

Tables 1 and 2 show the effect estimates for compensation claims by workers' demographics and work environment characteristics. Male workers had a statistically significant increase of 13% (95% CI: 3-23%) in overall claims during moderate-severity heatwaves, while no significant change was observed for female workers. No particular age group showed any significant increase in claims during heatwave periods (Table 1).

Regarding work experience, new workers (those with less than 1 year of experience at the time of the claim) showed a statistically significant increase in claims during moderate-severity heatwaves of 31% (95% CI: 10-55%). By contrast, there was no statistically significant increase in claims for experienced workers. Considering the industries, 'indoor industries' showed a statistically significant increase in claims overall during moderate-severity heatwaves (RR 1.09, 95%CI: 1.10-1.17), while 'outdoor industries' showed elevated risks, but not statistically significant risks (RR 1.05, 95% CI: 0.83-1.34). In particular, an increase of 8% (95%CI: 1-16%) was observed for claims among workers in the 'manufacturing industry' during low-intensity heatwaves (Table 1).

Positive associations were also observed during moderate-severity heatwaves for workers in medium-sized enterprises i.e. businesses with 20-199 employees (RR 1.15, 95%CI: 1.01-1.30), labourers (RR 1.21, 95%CI: 1.04-1.39), workers exposed to electrical hazards (RR 1.43, 95%CI: 1.15-1.79) and those working in dangerous locations (RR 3.17, 95%CI: 1.38-7.26).

Injuries occurring between 12 and 2pm increased during moderate-severity heatwaves (RR 1.39, 95% CI: 1.13-1.70) and this was also evident using the HWD2 definition (RR 1.11, 95%CI: 1.02-1.21). Also, there was a two-fold increase in injuries occurring between 6 and 8pm during high-severity heatwaves (Table 2). Notably, there was an increase in claims observed among workers from worksites located in the outer suburbs, while those in the central business district (CBD) had no increased risk.

3.2.3 Cross-validation

Using cross-validation methods, the two metrics used to define heatwaves (EHF and maximum temperature) were found to be similar predictors of heat-related outcomes (Figure 2).

4. Discussion

In this study of the effects of heatwaves on work-related injuries and illnesses in a temperate Australian city, concordant estimates were obtained using two population-based data sources. To the best of our knowledge, this study is the first of its kind to investigate and provide both supporting and new evidence on how heatwaves of varying severity, as defined using the Australian Bureau of Meteorology's updated metric for heatwaves, the Excess Heat Factor (EHF) may affect workers' health and safety.

This study has yielded several findings. Firstly, there was a consistent increase in workers' compensation claims and work-related ambulance call-outs during heatwaves of low-intensity and moderate-severity, and a non-significant decline during high-severity heatwaves. Secondly, moderate-severity heatwaves were significantly associated with an 8.8% increase in compensation claims, with the highest effect seen in injury claims, while a nonsignificant 20% increase was observed for work-related ambulance call-outs. These findings differ from previous studies (Rameezdeen and Elmualim 2017; Xiang et al. 2014b) that found no significant increase in claims during heatwave periods. However, the risk estimates were lower and protective in these previous studies which may be explained by the use of a stringent heatwave definition (three or more consecutive days of daily maximum temperature of 35°C). Thirdly, vulnerable groups during moderate-severity heatwaves in this study included male workers, new workers, laborers, those in medium-sized business (20-199 employees), and in industries with substantial indoor work and exposure to electrical hazards. Further, increased risk of work-related injuries and illnesses was observed during the high-severity heatwaves among workers in worksites located outside the CBD, while workers in the manufacturing industry were at risk even during low-intensity heatwaves.

Elsewhere, previous studies (Adam-Poupart et al. 2015; McInnes et al. 2017a; McInnes et al. 2017b; Morabito et al. 2006; Spector et al. 2016; Tawatsupa et al. 2013; Xiang et al. 2014c) have shown strong but variable evidence for a relationship between high ambient temperatures and occupational injuries, whereby injuries increase in a dose-response manner and decrease above a certain temperature threshold. Indeed, our findings of increasing injury risk during low-intensity and moderate-severity heatwaves which decline during high-severity heatwaves resonate well with this observation. This contrasts with studies on morbidity in the general population using EHF (Jegasothy et al. 2017; Scalley et al. 2015; Williams et al. 2018; Xiao et al. 2017) where the greatest impacts were seen with increasing severity of the heatwaves. This could be explained by the operation of workplace protective measures such as work ceasing work or being postponed during extreme temperatures (Rameezdeen and Elmualim 2017; Xiang et al. 2014c). Further, behavioral changes adopted by workers such as 'self-pacing' to reduce excessive heat strain, along with an increased awareness of heat impacts on health, may be associated with a reduced risk at the higher intensity heatwaves. Since 2009, heatwave warnings which have been implemented in Adelaide have appeared to reduce morbidity in the general population during severe heatwaves (Nitschke et al. 2016), and may have also influenced work practices.

Vulnerable groups identified in this study by gender, occupation, and size of business are similar to those found previously in Adelaide (Rameezdeen and Elmualim 2017; Xiang et al. 2014b). Lack of acclimatization to heat and the physical exertion required for the job may make new workers more vulnerable to injuries than those who are experienced (Gubernot et al. 2014; Rameezdeen and Elmualim 2017). This suggests that an acclimatization plan should be in place at workplaces along with heat stress training where appropriate for both new and experienced workers. Although urban areas are considered to be at high risk of heat-related health outcomes attributed to the 'urban heat island' effect, this was not evident in our findings. However, worksites located outside CBD identified as 'outer' suburbs had increased risk. This result is likely due to industries being located in the outer suburbs, as there was a more than three-fold increase in the risk of work-related injury or illness requiring ambulance attendance, in industrialized areas during heatwaves as reported in a study by Hansen et al. (2011).

Workers in industries where work is carried out in indoor environments were also found to be vulnerable during moderate-severity heatwaves. However, other studies have shown evidence that outdoor workers in industries such as 'agriculture, forestry and fishing', 'construction', 'mining' and 'electricity, gas and water' are typically at risk. Hot weather adds to the heat burden experienced by indoor workers in environments where there is process generated heat (e.g. foundries, bakeries, smelters, steel mills, glass factories, and furnaces) (Xiang et al. 2014a). If the workplace is not adequately cooled or ventilated, the added heat load can potentially compromise workers' health and safety (Xiang et al. 2014a). As efficient cooling methods such as air-conditioners or industrial fans may be impractical in such environments other personal cooling options and adaptive behaviors (e.g. rest breaks, job rotation, and altered work schedule) may need to be considered.

Although our data did not show any significant increase in the risk of health outcomes in outdoor industries, we note the elevation in risks for the electricity, gas and water and construction industries, which increased during moderate and high-severity heatwaves. This is consistent overall with a previous study undertaken in Adelaide (Xiang et al. 2014b). Furthermore, our finding of a 3-fold increase in the risk among those working in locations that are classified as being inherently dangerous (using the workers' environmental conditions classification-Human Resources & Skills Development Canada (2011)), such as construction sites, underground sites and erected support structures, confirms the vulnerability of these industries. The lack of statistical significance at the industry level might reflect the smaller sample size rather than the absence of an effect, and therefore the risks of injuries should not be ruled out.

Our results have the potential to inform unions, industry, and regulators in planning appropriate mitigation strategies for heatwave-related occupational health effects. The current Extreme Heat Plan for South Australia is focused on protecting population health during extreme heat events, which occur less frequently than moderate-severity heatwaves (SA Health 2016). However, our findings suggest workers are at risk before extreme levels are reached i.e. during the more frequent low and moderate-severity heatwaves. Hence, intervention strategies, policies and heat preparedness plans may need to consider lower thresholds for prevention measures in occupational settings.

Several limitations of this study need to be noted. Exposure misclassification was inherent in this study, as we assumed the entire study site to have the same EHF severity, and that the injury occurred at the workplace. Our results are also limited to one city, which may restrict its generalisability and it is possible that other cities with differing climates and working population characteristics may provide different results. However, the normalising effect of the

EHF severity technique design makes severity levels equivalent between locations, despite their differing climates.

Although humidity is not directly included in the EHF calculations, it is indirectly captured by its interaction with daily minimum temperature, which may extend its usefulness to humid environments (Adelaide typically has low humidity in summer) (Nairn and Fawcett 2014). Further studies in other geographic areas are thus warranted to validate the EHF metric and its utility in predicting occupational morbidities. This study was focused on the severity of heatwave events and therefore did not explore the effect of heatwave duration. Additionally, the use of administrative data, such as workers' compensation claims, is an underestimation of the overall burden and actual risk of injuries related to heatwaves experienced by workers in this region. It is possible that some occupational injuries not listed as a compensation claim, may be included in ambulance data, which is known to better capture minor injuries and those occurring among young workers (McInnes et al. 2014). However, the ambulance data used in this study were broadly coded as 'work-related' and descriptive details of the incidents were not available.

Nevertheless, the concordant estimates obtained from both sources of data is one of the key strengths of this study. In summary, this study extends the work of Xiang et al. (2014b) by examining the effects of heatwave intensity (using EHF) on work-related injuries and illnesses, and by using a case-crossover approach. In addition, we were able to examine factors such as workers' demographics, type of work and work environment characteristics, which may influence the occurrence of work-related injuries and illnesses. This approach has enabled us to obtain a more detailed picture of how heatwaves can affect workers' health and safety.

5. Conclusions

The findings indicate that working in hot weather is not only problematic for those working outdoors but also for those working indoors. Male workers and those new to the job appear to be at risk during heatwaves. Heatwave forecasting services may prove useful in the occupational setting to plan for and mitigate the effects of heatwaves on the health and safety of those working in hot conditions. Our data suggest that moderate heatwaves should be considered, in addition to severe heatwaves.

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Compliance with Ethical Standards

Ethical Statement

Ethics approval was obtained from the Human Research Ethics Committees of the University of Adelaide and SA Health.

Conflict of Interest

The authors declare that they have no conflict of interest.

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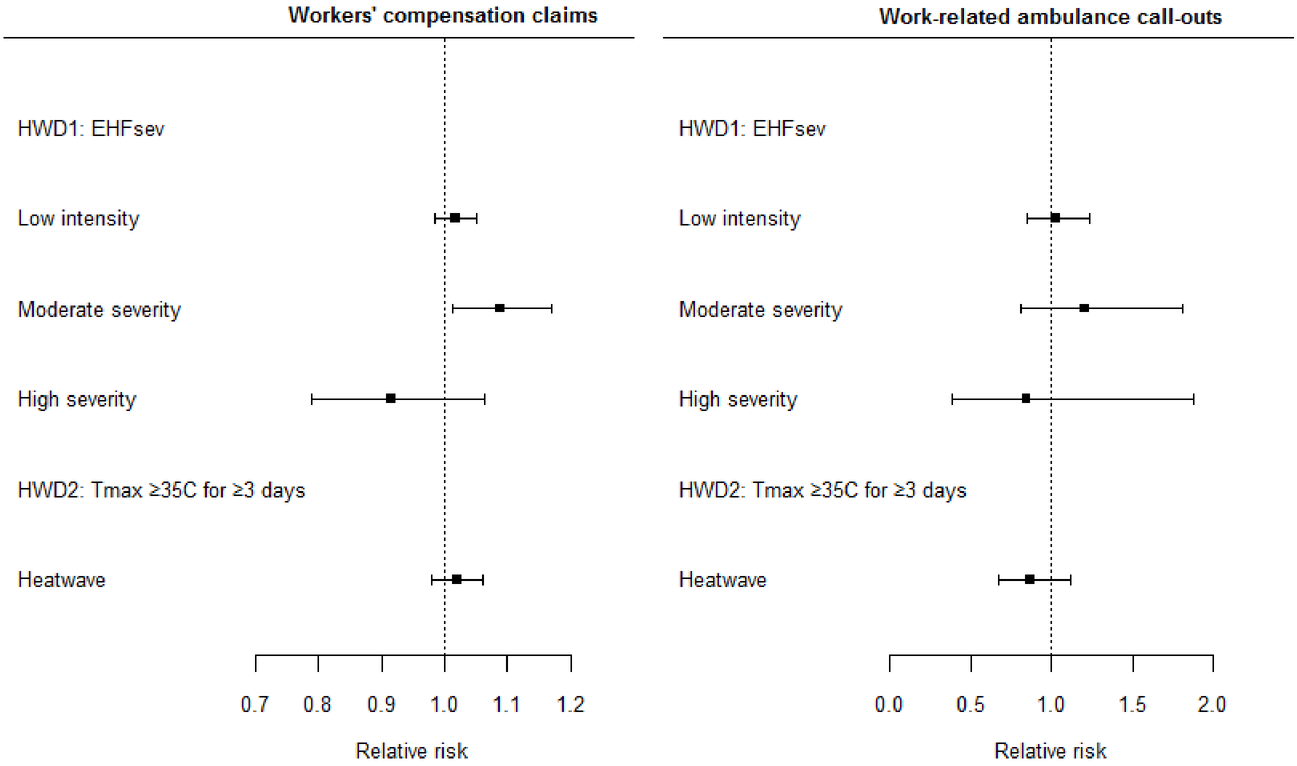

Figure 1. The association between heatwave severity and work-related injuries and illnesses, Adelaide Metropolitan area, October to March 2003 to 2013. (a) Workers' compensation claims; (b) Work-related ambulance call-outs.

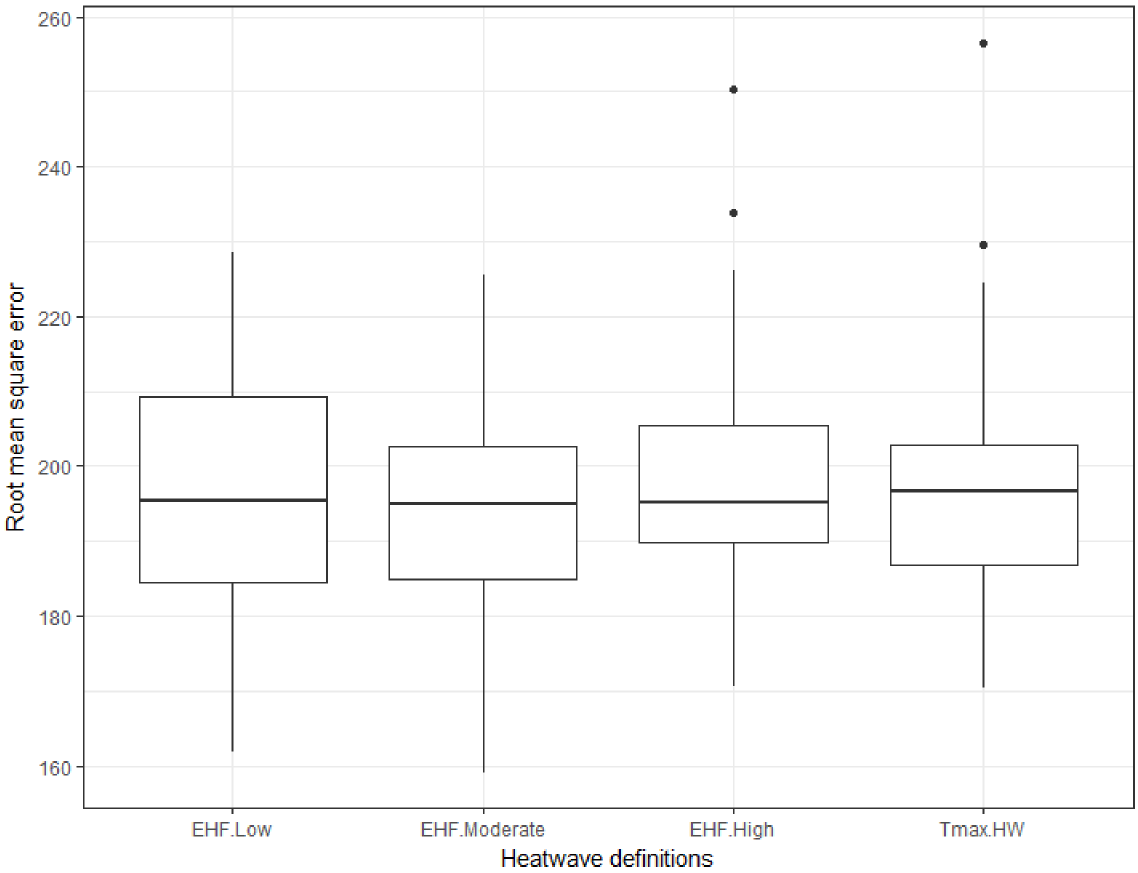

Figure 2. Boxplot of root mean square errors comparing the two heat wave metrics.

Here EHF.Low, EHF.Moderate and EHF.High constitutes HWD1 using EHFsev and Tmax.HW is HWD2.

Table 1. Effect estimates (Risk ratios) for the associations between workers' compensation claims and heatwave severity in Adelaide, October to March 2003 to 2013.

Exposure	Risk ratio (95%CI)			
	HWD1			HWD2
Claim characteristics	Low-intensity	Moderate-severity	High-severity	
All claims	1.01 (0.98,1.04)	1.08 (1.01,1.16)	0.91 (0.78,1.06)	1.02 (0.98,1.06)
Injury claims	1.02 (0.96,1.03)	1.10 (1.02,1.19)	0.92 (0.78,1.07)	1.02 (0.98,1.07)
Illness claims	1.13 (1.03,1.25)	0.90 (0.70,1.15)	0.97 (0.58,1.63)	0.94 (0.82,1.07)
Gender				
Female	0.98 (0.92,1.03)	0.99 (0.87,1.13)	0.76 (0.58,1.02)	1.01 (0.94,1.08)
Male	1.03 (0.99,1.07)	1.13 (1.03,1.23)	0.99 (0.82,1.18)	1.02 (0.97,1.07)
Age group				
15-24	1.00 (0.92,1.08)	1.15 (0.97,1.36)	0.89 (0.63,1.25)	1.08 (0.98,1.18)
25-34	0.99 (0.92,1.06)	1.11 (0.95,1.30)	1.14 (0.84,1.54)	1.00 (0.91,1.09)
35-54	1.01 (0.96,1.06)	1.08 (0.97,1.20)	0.88 (0.70,1.09)	1.01 (0.95,1.06)
>55 years	1.07 (0.98,1.16)	0.97 (0.78,1.18)	0.87 (0.57,1.31)	1.02 (0.91,1.13)
Worker experience				
Experienced worker	1.02 (0.98,1.05)	1.04 (0.96,1.13)	0.87 (0.74,1.03)	1.01 (0.97,1.06)
New worker	0.99 (0.91,1.07)	1.31 (1.10,1.55)	1.13 (0.79,1.61)	1.03 (0.94,1.14)
Industry location				
Outdoor	1.04 (0.94,1.16)	1.05 (0.83,1.34)	1.38 (0.78,2.31)	1.11 (0.98,1.27)
Agriculture, Forestry, Fishing & Hunting	0.95 (0.66,1.37)	1.29 (0.57,2.88)	0.11 (0.01,1.05)	0.98 (0.62,1.54)
Construction	1.06 (0.94,1.19)	1 (0.76,1.31)	1.46 (0.79,2.71)	1.06 (0.92,1.23)
Electricity, Gas & Water	0.88 (0.6,1.29)	1.48 (0.65,3.35)	2.53 (0.43,14.89)	1.46 (0.92,2.30)
Mining	1.21 (0.81,1.82)	1.13 (0.47,2.69)		1.77 (1.03,3.02)
Indoor	1.01 (0.98,1.04)	1.09 (1.01,1.17)	0.88 (0.76,1.03)	1.01 (0.97,1.05)
Communication	0.61 (0.16,2.37)	1.50 (0.14,16.23)		0.34 (0.06,1.91)
Community Services	0.97 (0.92,1.03)	1.13 (0.99,1.29)	0.84 (0.63,1.13)	1.05 (0.98,1.13)
Finance, Property & Business Services	1.08 (0.93,1.25)	1.24 (0.91,1.69)	0.66 (0.36,1.19)	1.04 (0.87,1.25)
Manufacturing	1.08 (1.01,1.16)	1.08 (0.93,1.26)	1.01 (0.76,1.33)	1.01 (0.93,1.10)
Public Administration & Defence	1.10 (0.91,1.34)	1.21 (0.77,1.90)	1.06 (0.46,2.46)	0.93 (0.73,1.19)
Recreation, Personal & Other Services	0.93 (0.82,1.07)	1.17 (0.89,1.55)	0.84 (0.42,1.69)	0.85 (0.72,1.01)
Transport & Storage	1.05 (0.92,1.19)	0.88 (0.64,1.21)	0.82 (0.42,1.62)	0.95 (0.80,1.12)
Wholesale & Retail Trade	0.99 (0.92,1.07)	1.02 (0.86,1.20)	0.88 (0.63,1.23)	1.06 (0.96,1.17)
Occupations				
Managers	0.95 (0.79,1.14)	0.99 (0.67,1.47)	0.79 (0.31,2.04)	0.83 (0.65,1.06)
Professionals	0.91 (0.82,1.02)	1.10 (0.85,1.43)	0.64 (0.35,1.17)	1.08 (0.95,1.24)
Technicians & trade workers	1.04 (0.97,1.11)	1.06 (0.91,1.23)	0.90 (0.66,1.23)	1.03 (0.94,1.12)
Community & personal	0.97 (0.89,1.05)	1.13 (0.93,1.37)	0.94 (0.62,1.41)	0.92 (0.83,1.03)
Clerical & administrative	1.06 (0.92,1.22)	0.86 (0.62,1.20)	0.80 (0.40,1.61)	0.96 (0.80,1.15)
Sales workers	0.84 (0.74,0.96)	0.99 (0.75,1.31)	1.38 (0.83,2.30)	1.04 (0.88,1.21)
Machinery operators & drivers	1.07 (0.99,1.15)	1.02 (0.86,1.22)	0.91 (0.65,1.29)	1.08 (0.98,1.19)
Labourers	1.08 (1.02,1.16)	1.21 (1.05,1.40)	0.89 (0.66,1.20)	1.06 (0.97,1.15)

Shaded cells denote statistical significant differences based on the 95% confidence interval; HWD1 based on EHF intensity and HWD2 based on T_{max} of 35°C for ≥3 consecutive days

Table 2. Risk ratios of workers' compensation claims by work environment characteristics by heatwave severity in Adelaide metropolitan area, October to March 2003 to 2013.

Exposure	Risk ratio (95%CI)			
	HWD1			HWD2
Work environment	Low-intensity	Moderate-severity	High-severity	
Size of business				
Small (<20 employees)	1.01 (0.93,1.10)	1.12 (0.93,1.35)	0.90 (0.63,1.29)	0.98 (0.88,1.10)
Medium (20-200 employees)	1.05 (0.99,1.11)	1.15 (1.01,1.30)	0.72 (0.56,0.94)	1.04 (0.97,1.12)
Large (>200 employees)	0.99 (0.95,1.03)	1.03 (0.93,1.14)	1.06 (0.86,1.31)	1.01 (0.96,1.07)
Worksite location				
Adelaide CBD	0.99 (0.91,1.06)	1.14 (0.96,1.35)	1.27 (0.87,1.85)	0.98 (0.89,1.08)
Adelaide Inner suburb	1.01 (0.97,1.05)	1.08 (0.98,1.18)	0.74 (0.61,0.89)	0.99 (0.94,1.05)
Adelaide Outer suburbs	1.05 (0.98,1.13)	1.05 (0.89,1.23)	1.36 (1.01,1.83)	1.11 (1.02,1.21)
Workplace hazards				
Dangerous chemical substances	1.10 (0.96,1.26)	1.09 (0.81,1.46)	0.97 (0.50,1.89)	1.10 (0.92,1.31)
Equipment, machinery, tools	0.90 (0.72,1.12)	1.18 (0.71,1.94)	1.80 (0.74,4.42)	0.90 (0.69,1.17)
Electricity	0.98 (0.88,1.08)	1.43 (1.15,1.79)	0.75 (0.47,1.20)	1.05 (0.92,1.20)
Dangerous locations	0.68 (0.44,1.06)	3.17 (1.39,7.26)	5.31 (0.70,40.13)	1.13 (0.68,1.87)
Multiple hazards	1.05 (0.99,1.11)	1.07 (0.94,1.23)	0.88 (0.68,1.15)	1.04 (0.97,1.12)
Time of injury				
00.00-01.59	1.07 (1.01,1.15)	0.93 (0.79,1.09)	0.77 (0.56,1.06)	0.85 (0.77,0.93)
02.00-03.59	1.15 (0.85,1.55)	0.83 (0.36,1.91)	0.79 (0.16,3.94)	1.02 (0.71,1.47)
04.00-05.59	1.06 (0.77,1.45)	0.67 (0.29,1.53)	1.06 (0.30,3.79)	0.85 (0.58,1.27)
06.00-07.59	0.97 (0.85,1.12)	1.30 (0.98,1.74)	1.14 (0.60,2.16)	1.26 (1.06,1.49)
08.00-09.59	0.98 (0.90,1.06)	1.12 (0.94,1.34)	1.04 (0.72,1.48)	1.07 (0.97,1.18)
10.00-11.59	0.99 (0.92,1.07)	1.04 (0.88,1.24)	1.19 (0.83,1.69)	1.03 (0.94,1.14)
12.00-13.59	0.99 (0.90,1.08)	1.39 (1.14,1.70)	0.58 (0.36,0.92)	1.16 (1.03,1.31)
14.00-15.59	1.06 (0.97,1.16)	1.14 (0.93,1.40)	0.86 (0.55,1.33)	1.02 (0.91,1.14)
16.00-17.59	0.94 (0.83,1.07)	0.97 (0.72,1.29)	0.78 (0.45,1.34)	1 (0.85,1.18)
18.00-19.59	1.08 (0.90,1.29)	1.03 (0.68,1.55)	2.13 (1.02,4.53)	1.20 (0.96,1.51)
20.00-21.59	1.15 (0.94,1.40)	0.99 (0.63,1.57)	1.16 (0.41,3.28)	1.02 (0.79,1.32)
22.00-23.59	1.04 (0.81,1.35)	1.28 (0.73,2.23)	0.71 (0.18,2.72)	1.19 (0.86,1.64)

Shaded cells denote statistical significant differences based on the 95% confidence interval. HWD1 based on EHF intensity and HWD2 based on T_{max} of 35°C for ≥3 consecutive days