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Geographical variation in risk of work-related injuries and illnesses associated with ambient temperatures: A multi-city case-crossover study in Australia, 2005-2016

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Abbreviations: RR: relative risk; DLNM: distributed lag non-linear model; T_{max}: maximum temperature; PAF: Population attributable fraction

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Abstract (289 words)

Background: The thermal working environment can have direct and in-direct effects on health and safety. Ambient temperatures have been associated with an increased risk of occupational injuries but it is unknown how the relationship can vary by weather, location and climate.

Objectives: To examine the relationship between ambient temperatures and work-related injury and illness compensation claims in three Australian cities: Melbourne and Perth (temperate climate) and Brisbane (subtropical climate) in order to determine how hot and cold weather influences the risk of occupational injury in Australia.

Methods: Workers' compensation claims from each city for the period 2005 to 2016 were merged with local daily weather data. A time-stratified case-crossover design combined with a distributed lag non-linear model was used to quantify the impacts of daily maximum temperature (T_{max}) on the risk of work-related injuries and illnesses.

Results: Compared to the median maximum temperature (T_{max}), extremely hot temperatures (99th percentile) were associated with a 14% (95%CI: 3-25%) increase in total workers' compensation claims in Melbourne, but there were no observed effects in Brisbane or Perth, with the exception of traumatic injuries that increased by 17% (95%CI: 3-35%) during extreme heat in Perth. For extremely low temperatures (1st percentile), there was a protective effect in Brisbane (RR 0.89; 95%CI: 0.81-0.98), while no effects were observed in Melbourne or Perth.

Conclusion: The relationship between injury and ambient temperature appears to be variable depending on location and climate. In general, work-related injuries and illnesses appear to be more common at higher temperatures than lower temperatures. Adopting adaptation and prevention measures could reduce the social and economic burden of injury, and formulating

effective measures for dealing with high temperatures should be prioritised given the predicted increase in the frequency and intensity of hot weather.

Introduction

Over the last few decades, numerous studies have evaluated the impacts of temperature extremes on human health and interest in assessing this relationship as a response to projected climate warming continues to grow. (1, 2) Exposure to extreme weather events such as heatwaves are associated with increased mortality and/or morbidity rates. (2-5) Several episodes of extreme weather events, for example, heatwaves in Chicago (1995), Europe (2003), Russia (2010), and Australia (2009 and 2014) have led to an increased awareness on the adverse health effects and have resulted in development of interventions and/or strategies targeted at specific population groups.(6-9) These specific population groups identified to be at-risk includes the elderly, children, those with chronic morbidities, lower socio-economic status, and those living in densely populated cities.(1, 10) In the context of a warming climate, the higher mean temperatures, increased summer temperature variability, and frequent, more intense, and longer duration of heatwaves worldwide are likely to exacerbate the health impacts of heat exposure with social and economic implications.(11)

Many studies have examined the health risks related to temperature extremes and epidemiological studies in particular, have contributed to the understanding and evidence of the potential adverse effects and associated risks of climate-related events on human health, and have identified the above mentioned populations of concern who are more at-risk. These epidemiological studies have described the relationship between ambient temperature and mortality/morbidity as a U-, V- or J-shaped curve, whereby mortality and morbidity rise progressively above or below a moderate temperature range, often referred to as the minimum mortality/morbidity temperature (MMT).(12) However, the effects of temperature, show geographical heterogeneity whereby cities with colder climates have generally greater heat effects while warmer cities have greater cold effects, reflecting population adaptation to local climate. (13)

An additional group at risk of adverse health consequences of temperature extremes is workers. In the occupational setting, interest in investigating the impacts of temperatures on workers' health and safety, particularly high temperatures, has been increasing since the fourth assessment report (2005-2007) of the Intergovernmental Panel on Climate Change (IPCC) where rising heat was first raised as a concern for workplaces. (14-18) In addition to heat-induced illnesses, work stress, physical discomfort and losses in work capacity and productivity, cumulative exposure to hot and cold temperatures at the workplace can place workers at risk of accidents/injuries. (15, 16, 18) Results of several experimental studies point towards an effect on accidents and injuries through diminished human performance due to factors such as fatigue, loss of alertness, lack of coordination and altered judgment, loss of dexterity and general discomfort. (15)

Most of the existing epidemiological studies have examined the association between temperature extremes and work-injuries using workers' compensation claims data. Studies in Italy (19, 20), Canada (21), China (22, 23), Thailand (24) and the USA (25-28), that mostly focussed on extreme heat show an increasing risk for injuries at higher temperatures, but that the association varies depending on the type of work and work location. Evidence regarding cold temperatures is limited to a small number of studies in Italy (29), the USA (30-32) and Spain (33). The latter study assessed the effects of heat and cold and estimated that 2.7% of all occupational injuries were attributable to non-optimal ambient temperatures, corresponding to an estimated 0.67 million person-days of work lost every year. The estimated annual economic burden to non-optimal ambient temperatures (both heat and cold) was estimated to be 370 million Euros or 0.03% of Spain's GDP. (33) Besides the specific economic burden related to occupational injuries due to non-optimum temperatures, various studies have also estimated an economic burden ranging between 0.1% and 0.5% of GDP from reduced work capacity and productivity related to heat stress. (18, 34-36)

Whilst studies (20-22, 26, 33) in different locations as mentioned above have examined the role of temperatures on occupational injuries, their results might not be generalizable to cities with different climate and population characteristics. There is a need to identify workers at-risk of injuries from thermal environments to provide an evidence base for developing local population and climate-specific workplace interventions and preventive measures to ease the impact of projected increased risks from extreme temperatures. This is important on the basis of climate change scenarios with average temperatures projected to increase by 0.6 to 1.5°C by 2030, with fewer cold extremes and more heat extremes. (37)

Australian workers experience a range of climates varying from warm and humid in the north of the country, through to cool and temperate in the south. (38) Australian studies of the adverse health effects of ambient temperatures on work-related outcomes have been mostly related to heat and based on the temperate climatic cities of Adelaide (39-43) and Melbourne (44-46). Evidence is currently lacking for other cities with a subtropical or tropical climate. Furthermore, there are no comparisons of work-related injuries and illnesses at moderately and extremely high-temperatures, and at cold temperatures. In this paper we examine: 1) the link between ambient temperatures and work-related injuries and illnesses in three major Australian cities with differing climates and experiences of extreme weather events; 2) the risk profile of workers in these cities; and 3) the attributable risk of work-related injuries and illnesses due to cold and heat.

Materials and Methods

Study setting

This study includes capital cities of three states in Australia, namely Melbourne (Victoria), Brisbane (Queensland) and Perth (Western Australia). Melbourne (37°81'S, 144°96'E) is on the southern east coast of Australia and is the country's second largest city with a mild temperate climate with warm summers and cool wet winters. (47) During summer (December to February) the average daytime daily maximum temperature (T_{max}) is 25.6 °C while in winter (June to August) the average T_{max} is 14 °C.

Brisbane (27°46'S, 153°02'E) is on the central east coast of Australia and is a sub-tropical city characterized by warm to hot weather for most of the year. The hottest months (December to February) can be very humid (average relative humidity of 65% to 70%) with average T_{max} of 29.3 °C, while winter is mostly mild and dry (average T_{max} 21.3 °C).

Perth (31°95'S, 115°86'E) is on the southern west coast and is characterized by a mix of warm temperate and typical Mediterranean climate with mild winters (average T_{max} 18.4 °C) and hot dry summers (average T_{max} 30.8 °C). (48)

These three cities combined comprised 37.4% or 9.4 million of Australia's estimated resident population in 2018 (Melbourne -4.9 million, Brisbane -2.4 million, and Perth -2.1 million) with an estimated employed labour force of 4.1 million. (49)

Data sources

Workers' compensation claims data

The data included all accepted workers' daily compensation claims for work-related injuries and illnesses (as determined by the insurer) lodged between 1 July 2005 and 30 June 2016 in the three cities. All injuries regardless of their severity (minor or major) were included, although those that occurred during commuting to and from work were excluded, as they are not compensable in all jurisdictions. These data were extracted from the National Dataset for Compensation Based Statistics (NDS3) collected by Safe Work Australia (SWA). The NDS3 is an amalgamation of case-level data supplied each year by jurisdictional workers' compensation schemes. Details about this database are provided elsewhere. (50) As effects of temperature are likely to be higher in those carrying out physical work and in outdoor environments, we used industrial classifications following the work of Xiang et al (2014) to categorise workers as working in either 'outdoor industries' or 'indoor industries'. Additionally, as in our previous study (43), we also categorized the physical job demands (strength) and the potential workplace temperature exposures at the occupational level using a validated cross-walk approach that has been described elsewhere. (44)

Meteorological data

Weather data including daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily mean temperature (T_{mean}), relative humidity, wind speed and solar radiation were obtained from the Australian Bureau of Meteorology. A single established weather station was selected to represent the weather conditions in each city, in line with previous studies. (51-53)

Study design

We investigated the impact of ambient temperature on work-related injuries and illnesses using a time-stratified case-crossover approach. This study design, where each case is their own control (54), is appropriate in occupational epidemiology (55) for studying acute outcomes related to transient environmental risk (e.g. temperature). The case-crossover design also controls for seasonal changes and long-term trends in injury risk that are unrelated to temperature. In contrast to similar studies (44, 45) and other mortality/morbidity studies (56, 57) that use a monthly strata of 28 days, we chose a short strata (control period) of 7 days. Several factors such as labour strikes, power outages, change in work setting, practice and/or tasks undertaken, and vacation periods may affect week-to-week numbers of workers. (44) Therefore, a shorter window than 28 days was needed to account for these week-to-week changes in the number of workers. In our strata, a case day (date of injury) is compared to 6 other referent days (days when the injury did not occur) within the same calendar week (Sunday to Saturday). Using this approach we examined the impact of ambient temperature on work-related injuries/illnesses by three domains: work, worker and work environment characteristics.

Statistical Modelling

The time-stratified case-crossover study design was combined with the distributed lag non-linear model (DLNM) to model the non-linear and delayed effect of temperature. (43, 58, 59) The city-specific exposure-response and lag-response relationship between ambient temperature and work-related injuries were both modelled with a natural cubic spline with 3 degrees of freedom (df) for temperature and 2 df for lagged effects. (43) The maximum lag was set to 6 days as the longest possible delay between temperature exposure and work-related injuries.

We included relative humidity in the models, as Brisbane has a hot and humid climate during summer and higher humidity levels may lead to over-heating of the body due to slower evaporation of sweat. (60)

Tests of modelling assumptions were undertaken, including checking the residuals for normality, outliers and autocorrelation, and collinearity checks using the variance inflation factor. The initial check of residuals led to the modelling of 'first day of the financial year' (1 July) and 'New Year's day' as separate variables. Models were also adjusted for day of the week, 'Christmas Day', and other public holidays using binary indicator variables. These adjustments controlled for a reduction in worker numbers on weekends and holidays. All modelling choices and selection of degrees of freedom were determined using the Akaike Information Criterion. (59, 61)

The median value of daily maximum temperature for each city over the study period was used as the centering value (baseline temperature) for calculating relative risks (RRs) at the

1st (extreme cold), 10th (moderate cold), 90th (moderate hot) and 99th (extreme hot) temperature percentiles in line with previous studies. (12, 33, 43, 62-64)

Several sensitivity analyses were used to test the robustness of the above modelling choices for the case-crossover design combined with the DLNM model. These included: varying the degrees of freedom for temperature and lag dimensions, excluding relative humidity, and varying the temperature indices by using apparent temperature, Humidex, Heat Index, Wet Bulb Globe Temperature and Universal Thermal Comfort Index.

Attributable risk

We calculated the number of injuries attributable to temperature and the population attributable fraction using a previously defined method. (65) In short, the total number of claims attributable to temperature (AN) in each city was calculated using the minimum T_{max} in each city as the reference temperature to find the number of claims that could be avoided if the temperature remained at its coldest. The minimum T_{max} in each city represents the lowest point on the exposure-response curve, is in line with previous studies (12, 65) calculating attributable mortality/morbidity risks of temperature. The ratio of AN with the total number of claims gives the population attributable fraction (PAF). Empirical 95% confidence intervals were obtained for PAF and AN through 5000 Monte Carlo simulations. (65)

Results

Descriptive

Between 1 July 2005 and 30th June 2016, a total of 798,831 accepted workers' compensation claims were reported in the three cities: i.e. Melbourne -258,379, Brisbane -260,730 and Perth- 279,722. Across the cities, the claimants were predominantly males (66%) and aged between 35 and 54 years (47%). About 51% of claims occurred in the 'manufacturing' (18%), 'healthcare and social assistance' (13%), 'construction' (10%) and 'retail trade' (10%)

industries. In Brisbane and Melbourne, more than half of the claims were ‘major’ (57%) involving a week or more of work days lost, while in Perth the majority of claims were minor i.e. less than a week of work days lost (66%). The majority of the claims (91%) were injury-related while 9% were illness-related. Over half of the claims (56%) were due to musculoskeletal injuries, followed by traumatic injuries and fractures (34%). Table S1 summarises the characteristics of compensation claims.

Over the years 2005 to 2016, the daily average T_{max} was 21.1°C (range 9.2 - 46.4 °C) for Melbourne, 26.4 °C (range 12.6 - 40.2 °C) for Brisbane, and 25 °C (range 12.8 - 44.4 °C) for Perth. The mean and median (50th percentile) values of daily maximum, minimum, and mean temperatures (T_{max}, T_{min} and T_{mean}) were higher in Brisbane, while Melbourne had the highest maximum temperatures. The average daily relative humidity ranged from 64% in Melbourne to 70% in Brisbane (Table 1).

Table 1 Summary statistics of daily weather variables for Brisbane, Melbourne and Perth, 2005 to 2016.

City	Meteorological indicator	Mean	Minimum	Maximum	Percentiles					
					1st	10^{th}	50^{th}	90^{th}	99^{th}	IQR
Brisbane	Daily T_{max} (°C)	26.4	12.6	40.2	17.7	21.4	26.8	31	34.7	5.7
	Daily T_{min} (°C)	16.4	2.6	26.5	6.2	10	16.9	22	24.5	7.4
	Daily T_{mean} (°C)	21.4	10.7	31.5	13.1	16	21.8	26.3	28.9	6.4
	Daily RH (%)	69.5	19.8	98	39.1	57.3	70	81.7	91.8	11.1
Melbourne	Daily T_{max} (°C)	21.1	9.2	46.4	11.4	14.2	20.0	29.9	38.9	8.4
	Daily T_{min} (°C)	11.9	0.6	28.6	3.5	6.6	11.7	17.5	22.4	6
	Daily T_{mean} (°C)	16.5	6.4	35.5	8.4	10.8	16	23.4	29.4	7.1
	Daily RH (%)	63.8	19.1	100	33	49.5	64.1	78.2	88.6	15.4
Perth	Daily T_{max} (°C)	25	12.8	44.4	15.3	18	23.8	34.2	40.1	9.1
	Daily T_{min} (°C)	12.9	-0.7	29.7	2	5.9	13.1	19.5	23.8	7.4
	Daily T_{mean} (°C)	18.9	7.4	35.4	9.6	12.7	18.3	26.3	31.2	7.9
	Daily RH (%)	64.7	20.5	95.2	30.8	44.1	66.8	81.2	90.3	19.7

Exposure-response relationship

Overall

The cumulative association between daily maximum temperatures and work-related injuries and illnesses presented as relative risk (RR) for each city, is shown in Figure 1. There was a heterogeneous pattern between cities in the effects of heat, with increasing injury risk at the extremes, while cold effects were similar in each city with decreasing injury risks at the coldest extremes.

Relative to the median, increasing T_{max} in Melbourne was associated with an increase in injury risk, with relative risks of 1.05 (95%CI: 0.99-1.10) for moderately hot (90^{th} percentile) and 1.14 (95%CI: 1.03-1.25) for extremely hot (99^{th} percentile) temperatures. In other cities the corresponding RR for injuries for moderately hot and extremely hot temperatures were

0.96 (95%CI: 0.93-1.01) and 0.98 (95%CI: 0.89-1.09) in Brisbane, and 0.98 (95%CI: 0.93-1.04) and 1.01 (95%CI: 0.93-1.11) in Perth, respectively. In Brisbane and Perth, we observed a 'comfort zone' of temperature (above the 50th percentile of T_{max}) where injury risks were decreased (RRs < 1), before increasing (RRs >1) at the upper temperature range of 37°C and 37.5°C in Brisbane and Perth, respectively. Protective associations were observed on cold days in Brisbane, with a RR of 0.89 (95%CI: 0.81-0.98), at the 1st percentile versus relative to the median T_{max}. A non-significant risk reduction was seen on cold days in the other cities compared to the median T_{max}, with corresponding RRs of 0.99 (95%CI: 0.90-1.09) in Melbourne and 0.96 (95%CI: 0.88-1.05) in Perth, respectively.

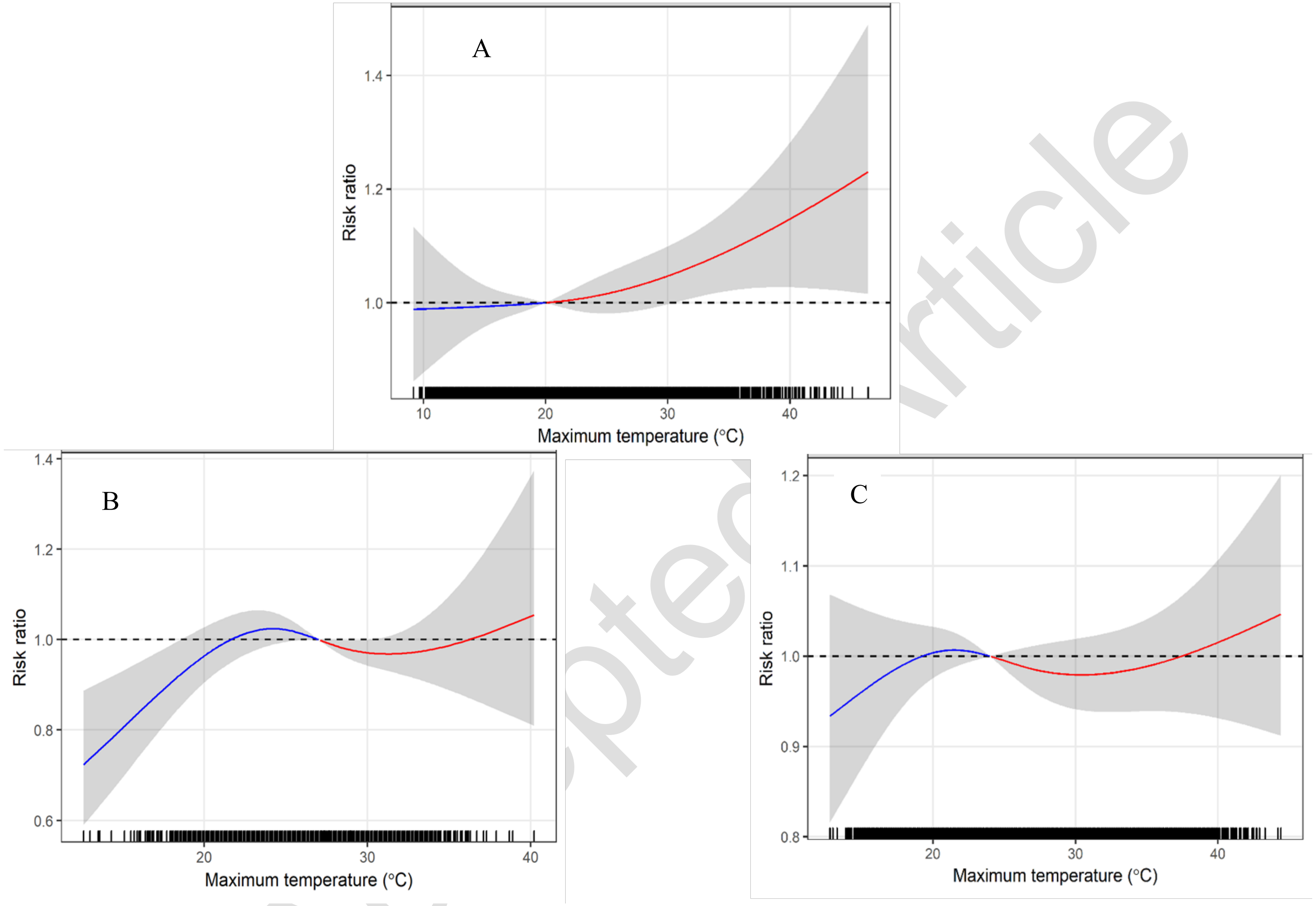

Figure 1. Relative risks of workers' compensation claims associated with daily maximum temperature (°C) relative to median T_{max} of (A) 20°C in Melbourne, (B) 27°C in Brisbane and (C) 24°C in Perth, using data from 1 July 2005 to 30 June 2016.

The effects of ambient temperatures on claims stratified by workers' demographics, work and work environment characteristics for Melbourne are shown in Table 2. In Melbourne, young workers (RR 1.18, 95%CI: 1.03-1.36) and those in 'regulated indoor climates' (RR 1.07, 95%CI: 1.01-1.14) had higher risk of work-related injuries and illnesses on moderately hot days (90th percentile vs. median T_{max}). Increased risks of work-related injuries and illnesses during extremely hot temperatures (99th percentile) were observed for female workers (RR 1.27, 95%CI: 1.07-1.15), those aged 25 to 34 years (RR 1.25, 95%CI: 1.01-1.55), workers who are not an apprentice/trainee (RR 1.14, 95%CI: 1.03-1.26) and workers 'in a vehicle or cab' (RR 1.34, 95%CI: 1.10-1.63). Workers in 'indoor industries' and in 'medium-demanding' occupations were susceptible to both moderately and extremely hot temperatures with the highest mean RR observed for 'Transport, postal and warehousing' industry (RR 1.59, 95%CI: 1.18-2.13, results not shown).

Supplementary Table S2 shows corresponding effects of ambient temperatures on claims in Brisbane and Perth where there was no statistically significant changes in risk for most subgroups. Industry-specific analysis showed higher RRs during extremely hot temperatures for 'Agriculture, forestry and fishing' (RR 1.91, 95%CI: 0.72-5.03) and 'Transport, postal and warehousing' (RR 1.37, 95%CI: 0.99-1.90) in Brisbane, and 'Electricity, gas and water' (RR 1.53, 95%CI: 0.70-3.37) in Perth; however, these were not statistically significant (results not shown).

Consistent with the overall pattern observed at cold temperatures in Melbourne, workers in 'medium-demanding' occupations and 'indoor' and 'outdoor' industries had lower risk of work-related injuries and illnesses relative to the median T_{max} (Table 2), while in Brisbane 'male workers', those aged 15-24 years, workers in 'outdoor' industries and 'heavy-demanding' occupations had lower risk (Table S2). No change in risks was observed in Perth for any of these subgroups (Table S2).

Injury and illness characteristics

In Melbourne, claims with the injury characteristics classified as 'falls, trips and slips of a person' increased during moderately and extremely cold temperatures (RR 1.11; 95%CI: 1.00-1.22 and RR 1.24; 95%CI: 1.01-1.52, respectively, results not shown), while those due to 'being hit by moving objects' increased during moderately and extremely hot temperatures (RR 1.14; 95%CI: 1.01-1.29 and RR 1.33; 95%CI 1.03-1.71, respectively, results not shown). Claims due to 'heat, electricity and other environmental factors' increased during moderately hot temperatures (RR 1.63; 95%CI: 1.09-2.45), while those due to 'mental stress' increased during extremely hot temperatures (RR 1.54; 95%CI: 1.01-2.32, results not shown). In Brisbane no specific types of injuries were significantly increased during hot temperatures, while in Perth traumatic injuries increased during extremely hot temperatures (RR 1.17; 95%CI: 1.02-1.35, results not shown). By further stratifying the traumatic injuries data for Perth, we found that workers who were not an apprentice/trainee were at risk at moderately hot (RR 1.15, 95%CI: 1.05-1.27) and extremely hot temperatures (RR 1.31, 95%CI: 1.10-1.55), while workers in the construction industry (RR 1.61, 95%CI: 1.09-2.39), retail trade industry (RR 1.60, 95%CI: 1.07-2.38) and 'medium-demanding' occupations (RR 1.54, 95%CI: 1.22-1.93) were at risk during extremely hot temperatures (results not shown).

Table 2 The relative risks for workers' compensation claims in hot and cold temperatures stratified by claims characteristics in Melbourne metropolitan area, 2005 to 2016 (RR with 95% CI).

Exposure[a]	Extreme cold[b]	Moderate cold[c]	Moderate heat[d]	Extreme heat[e]
Claim severity				
Minor claims	0.82 (0.68, 0.99)	0.88 (0.80, 0.96)	1.15 (1.04, 1.27)	1.17 (0.95, 1.44)
Major claims	1.05 (0.94, 1.17)	1.03 (0.97, 1.09)	1.02 (0.96, 1.07)	1.12 (1.02, 1.26)
Gender				
Male	1.04 (0.92, 1.17)	1.02 (0.95, 1.08)	1.03 (0.97, 1.10)	1.06 (0.93, 1.21)
Female	0.90 (0.77, 1.05)	0.95 (0.88, 1.03)	1.06 (0.98, 1.15)	1.27 (1.07, 1.50)
Age group (years)				
15-24	1.14 (0.86, 1.50)	1.02 (0.89, 1.16)	1.18 (1.03, 1.36)	1.15 (0.86, 1.53)
25-34	1.05 (0.85, 1.29)	1.02 (0.92, 1.13)	1.08 (0.96, 1.20)	1.25 (1.01, 1.55)
35-54	0.96 (0.84, 1.09)	0.98 (0.92, 1.05)	1.02 (0.94, 1.09)	1.12 (0.97, 1.29)
>55	0.91 (0.73, 1.15)	0.95 (0.85, 1.07)	1.01 (0.90, 1.14)	1.05 (0.82, 1.33)
Worker experience				
Apprentice/Trainee	1.06 (0.51, 2.17)	1.02 (0.72, 1.45)	0.97 (0.66, 1.41)	0.87 (0.40, 1.87)
Other	0.98 (0.90, 1.09)	0.99 (0.94, 1.04)	1.05 (0.99, 1.10)	1.14 (1.03, 1.26)
Potential workplace temperature exposure				
Regulated indoors	0.95 (0.89, 1.02)	0.98 (0.92, 1.03)	1.07 (1.01, 1.14)	1.04 (0.98, 1.11)
Unregulated indoors and outside	0.66 (0.32, 1.35)	0.75 (0.40, 1.39)	0.73 (0.38, 1.42)	0.99 (0.49, 2.00)
In a vehicle or cab	0.86 (0.70, 1.05)	1.00 (0.84, 1.20)	1.02 (0.85, 1.23)	1.34 (1.10, 1.63)
Multiple locations	0.94 (0.85, 1.06)	1.03 (0.93, 1.13)	0.96 (0.87, 1.07)	0.99 (0.88, 1.11)
Physical demands				
Limited (≤ 5kg)	0.94 (0.78, 1.13)	0.95 (0.90,1.00)	1.03 (0.98, 1.09)	1.06 (0.87, 1.30)
Light (5-10kg)	0.92 (0.75, 1.14)	0.99 (0.94,1.06)	1.00 (0.94, 1.06)	0.99 (0.80, 1.24)
Medium (10-20kg)	0.96 (0.82, 1.13)	0.94 (0.90, 0.98)	1.05 (1.01, 1.09)	1.23 (1.03, 1.47)
Heavy (>20 kg)	1.17 (0.94, 1.45)	1.01 (0.95,1.07)	1.01 (0.95, 1.07)	1.24 (0.98, 1.55)
Industry				
Indoor	0.95 (0.90, 1.01)	0.97 (0.94, 0.99)	1.04 (1.01, 1.07)	1.06 (1.01, 1.12)
Outdoor	0.84 (0.72, 0.99)	0.92 (0.86, 0.99)	0.96 (0.89, 1.04)	0.96 (0.82, 1.14)

Abbreviations: CI confidence interval; RR, relative risk. Shaded cells indicate statistically significant results.

a. All temperatures were compared with the median maximum temperature of 20.0ºC.

b. The first percentile of temperature (11.4ºC)
c. The 10^{th} percentile of temperature (14.3ºC)
d. The 90^{th} percentile of temperature (29.9ºC)
e. The 99^{th} percentile of temperature (38.9ºC)

Population attributable fraction

The population attributable fractions for workers' compensation claims attributable to temperature were 1.9% (95%CI: 10.3, 13.4%) in Melbourne, 26.5% (95%CI: 10.2, 40.1%) in Brisbane and 5.7% (95%CI: 6.1, 16.9) in Perth (Table 3). The corresponding number of claims attributed to temperatures in these cities for the whole study period (11 years) was calculated to be 5,137 claims in Melbourne (467 claims/year), 69,442 claims in Brisbane (6312 claims/year) and 16,467 claims in Perth (1497/year).

Table 3. The attributable risk numbers (AN) and population attributable fractions (PAF) and 95% confidence intervals using the lowest maximum temperature in Melbourne, Brisbane and Perth, 2005 to 2016.

Exposure / City	Reference Temperature	AN n (95%CI)	PAF % (95%CI)
Melbourne	9.2 ºC	5137 (-27,478 to 34,923)	1.98 (-10.3,13.4)
Brisbane	12.6 ºC	69,442 (27,967 to 104,649)	26.51 (10.2,40.1)
Perth	12.8 ºC	16,467 (-17,959 to 46,612)	5.71 (-6.1,16.9)

Sensitivity analyses

Similar estimated effects were obtained for the range of sensitivity analyses, including other temperature metrics (supplementary material, Table S3). It should be noted that during extremely cold temperatures in Brisbane a protective effect was found when using maximum temperature (and other indices) as the exposure variable, whereas elevated risk ratios were found when using mean or minimum temperature. Varying the degrees of freedom for T_{max} and lag dimensions did not substantially change any results (results not shown).

Discussion

In this study, the associations between ambient temperature and work-related injuries and illnesses were explored and quantified using workers' compensation claims data from three

Australian cities with differing climates. Our results provide both supporting and new evidence regarding the occupational impacts of hot and cold temperatures.

The key findings can be summarised as follows. Firstly, the exposure-response relationships varied between the cities, particularly in Melbourne where a stronger effect of increasing temperatures (moderate and extreme) was found. In contrast, claims increased only slightly in Brisbane and Perth when temperatures were close to, or above the reference level of extreme hot temperatures (99th percentile). Secondly, cool to cold temperatures (moderate and extreme) were associated with lower risks of overall claims in all three cities, with Brisbane showing a large protective association. However, specific injuries due to 'falls, trips and slips' increased on cold days in Melbourne. Thirdly, worker subgroups vulnerable to injuries during warm or hot weather were not those in heavy physically demanding occupations and working outdoors, as expected, but were those in 'medium' strength occupations and those working in 'regulated indoors' and 'vehicle or cab' environments. Finally, the burden of claims attributable to temperatures appears to be considerably higher in a sub-tropical location than temperate locations.

The differences in risks across the cities warrants further investigation, because it suggests that there are location or population-specific factors that influence the impact of temperature on workers' health. This is in contrast to studies examining temperature and mortality risk in Australia, which have reported a similar relationship for Brisbane, Melbourne and Sydney. (2, 12) It is possible that these differences are related to workplace factors; for example, although there exists harmonised model workplace health and safety (WHS) legislations, there are variances in how they are implemented and enforced across states and territories. Furthermore, there are likely differences between the cities in relation to industry or employment profiles, which may also contribute to differences in the exposure-response curves.

Our finding of a stronger heat effect on workers' claims in Melbourne is consistent with previous studies (44, 45) in this city and also with a previous study in Adelaide (43), which also has a temperate climate. The different relationship to that observed in Brisbane and Perth may be due to climatic or non-climatic factors. Melbourne is situated at a higher latitude than Perth and Brisbane, with a cooler climate overall, yet more variable temperatures in summer. These factors may contribute to the increased sensitivity of workers, who may be less acclimatised to high temperatures. Health effects have been reported to be greater in other cities with cooler climates but higher temperature variability in summer. (66, 67) Our results for Melbourne are consistent with this observation, and suggest that, at least for extreme hot temperatures, these factors matter. Although we do not know the prevalence of workplace air-conditioning, Melbourne has a lower prevalence of any type of household air-conditioning and higher prevalence of heaters than Brisbane and Perth based on reports by the Australian Bureau of Statistics. (68) This indicates that adaptation to cold may be better than to heat in Melbourne. However, the role of individual physiological and behavioural adaptations in this study were not explored due to the ecological study design and lack of such data within the workers' compensation database. Further investigation is needed in order to disentangle and identify factors that may have contributed to the observed heterogeneity in the heat effects.

The worker subgroups most vulnerable to hot days in Melbourne included: 'workers who are not an apprentice/trainee', 'female workers' and 'young workers'. These findings are largely similar to those reported by previous studies (40, 43) with some notable variations. Although several studies (26, 40) have shown male workers to be at greater risk due to their occupational profiles, our results indicate a pronounced effect for female workers during moderately and extremely hot days. Industrial sectors with mostly indoor activities, which have a higher proportion of female workers showed stronger heat effects than industries with mostly outdoor activities.

The finding that outdoor workers were not at elevated risk in Melbourne was unexpected as it contrasts with previous studies (40, 41, 43), and suggests the existence of heat stress policies, better acclimatisation status or greater awareness of risks posed by hot weather have likely reduced the risks for those working in industries with mostly outdoor activities. Consistent with the study of McInnes et al (2017)(44) we found that workers in 'regulated indoor climates' and 'in a vehicle or cab' but not in 'unregulated indoor and outside', had increased risks of injury. Although a regulated indoor climate includes work carried out in air-conditioned environments, occupational health problems may arise in workers acclimatised to cooler workplaces if the air-conditioning system fails as they may have reduced capacity for physiological regulation to higher temperatures.(69) It is also possible that workers may not be indoors all the time, thereby being subject to the effects of heat stress and injury when required to work outdoors. Similarly, 'vehicle or cab' environments may not necessarily be air-conditioned, and drivers may need to spend considerable time outside of the vehicle. Furthermore, it is also important to note that the 'unregulated/regulated indoor' and 'vehicle or cab' classification of work environments is a crude measure of workers' potential temperature exposure.

Our finding of an association between T_{max} and medium physically demanding occupations in Melbourne resonates with a study in Quebec (21) and Adelaide (43) but contrasts with a previous study in Melbourne (44), where associations were observed only for heavy physically demanding occupations. These findings emphasise that the level of physical strength required by the occupation and other personal risk factors such as acclimatisation and awareness of the health risks of hot weather may be important effect modifiers for injuries on hot days for those working primarily indoors or in industries with mostly indoor activities.

The lack of a significant association between hot temperatures and claims in Brisbane was an unexpected finding, as this city experiences higher levels of humidity on summer days. This finding contrasts with a study in Guangzhou, China, a city with similar climate to Brisbane. (22) Humidity limits evaporation, a major heat loss mechanism, and this would be expected to place workers at greater risk of injuries than in locations where humidity levels are comparatively low (Melbourne and Perth). However, the role of humidity did not seem to influence our results, either when controlling for it with T_{max} or its inclusion in composite indices (e.g. WBGT), possibly because the Brisbane working population is likely acclimatised to high temperatures and humidity in summer.

There appears to be a broader ‘comfortable working zone’ in terms of temperature in Brisbane and Perth, where the risk of work-related injuries and illnesses is lower. As previously mentioned, this possibly indicates adaptation to local climatic conditions either through physiological, technological and or behavioural acclimatisation of the workers (10, 67, 70, 71), or more effective occupational work health and safety practices. However, once temperatures rise above the ‘comfortable working zone’, the risk ratios were somewhat elevated (albeit non-significantly) at extreme temperatures (37 °C in Brisbane and 38 °C in Perth). This suggests that workers in Brisbane and Perth are still likely to be affected by extreme heat in their climatic region. This is clearly evident in our finding that ‘traumatic injuries’ increased by 17% during extreme hot days in Perth. Previous studies in Adelaide, a city with comparable climate to Perth, reported that traumatic injuries such as ‘wounds, lacerations and amputations’ and ‘burns’ increased during high temperatures and heatwave periods. (41, 43) Similar to studies in Adelaide, the at-risk worker subgroups for traumatic injuries during extremely hot temperatures in Perth were those in the construction industry, workers in medium-demanding occupations, and workers who are not an apprentice/trainee.

In contrast to the effects of heat, our results indicate that injuries appear to be reduced during cold days in all cities. This protective effect at cold temperatures contrasts with a recent study in Spain (33), where a U-shaped curve was found between ambient temperature and risk of occupational injuries. Our results do indicate that 'falls, trips and slips' increased in Melbourne during moderate and extreme cold days, which is in agreement with other studies. (29, 30) It should also be noted that elevated risks at extremely cold temperatures were apparent when minimum temperature was used as the exposure variable in Brisbane. Minimum temperature is a more effective indicator of low overnight and early morning temperatures, and these are likely to impact those who work non-traditional workhours.

Regarding the numbers of claims that could be attributed to temperature, we found that overall PAFs of work-related injuries and illnesses was considerably lower in Melbourne and Perth, despite the increased risk of work-related injuries and illnesses in Melbourne at extremely hot temperatures. The high PAF for Brisbane likely occurs because of the much lower risk of work-related injuries and illnesses is at the lowest temperature, compared to which every day is associated with an increased risk.

Study limitations

This study has a number of limitations. The retrospective ecological nature of the study confines our ability to deduce the causal association of ambient temperature with work-related injuries. Consistent with other ecological time-series and case-crossover studies, we relied on temperature data from an outdoor weather station as a surrogate for personal exposure, which fails to account for the spatial and temporal variations of ambient temperatures in workplaces. This introduces misclassification of exposure, as the temperatures to which workers were exposed before the injury may not necessarily reflect that measured at the weather station. Additionally, the claims data analysed in this study are limited to workers who had "accepted compensation claims" and excludes rejected claims and injuries for which no claim was lodged. Thus, the use of an administrative dataset not intended for research purposes does not capture the total burden of work-related injuries and illness for the general labour force. Lastly, this study is focussed on three cities of Australia, two with a temperate climate and one with a sub-tropical climate. This limits generalizability of findings, and further investigations are needed for other cities in Australia with tropical climates that may have different effects to that observed in the study sites.

Despite these caveats, this study has a number of strengths. The findings have characterised the relationships between ambient temperature and occupational injuries in three large Australian cities in different climatic zones, and quantified the associated attributable burden. Consistent definitions, study periods, procedures and statistical methods were used for each city thereby enabling direct inter-jurisdictional comparisons. A further strength is the use of flexible distributed lag non-linear models (DLNM), combined with a time-stratified case crossover study design that accounts for (i) the non-linear, delayed effects of daily ambient temperatures, and (ii) the lack of denominator information. The inclusion of all claims including those classified as "minor" and "major" is a further strength of this study.

Our findings have public health implications in the context of a warming climate. RCP4.5 scenarios predict that among the three study sites, the predicted annual temperature rise and annual number of days above 35 ºC and 40 ºC for 2030 and 2090 is highest in Brisbane followed by Perth and Melbourne. (72) These projections and our findings indicate that location and climate-specific targeted intervention strategies are needed to inform location-specific action WHS plans for hot weather. It is also possible that the results from this study could be extended to other cities with similar climatic conditions to support the development of extreme weather plans. Future studies using qualitative methods could be conducted to provide more in-depth analysis and exploration of the many complex factors that contribute to heat or cold related injuries, and how they may differ by worker populations and location.

Conclusion

Our study contributes to the growing body of research documenting the relationships between occupational health risks and ambient temperatures. Our results confirm that high ambient temperatures pose a risk for workers' health and safety by increasing the occurrence of work-related injuries in Melbourne, especially at hot extremes. Although exposure to hot temperatures appears to have a lesser effect on work injuries in Brisbane and Perth, the burden attributable to temperature appears to be higher in sub-tropical Brisbane. Our results indicate that cooler day time maximum temperatures are associated with reduced risks to workers in all three cities. While workers' health and safety should be a priority at all times of the year, our results suggest that there should be particular attention as temperatures increase.

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Supplementary Material

Geographical variation in occupational injury risks associated with ambient temperatures: A multi-city case-crossover study in Australia, 2005-2016

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Contents

Claim characteristics

Table 1 Description of the claims dataset, 2005-2016.

Classification	Combined n (%)	Brisbane n (%)	Melbourne n (%)	Perth n (%)
All claims	798,831	260,730 (32.6)	258,379 (32.3)	279,722 (35.0)
Gender				
Female	274,580 (34.4)	95,037 (36.5)	937,37 (36.3)	85,806 (30.7)
Male	524,251 (65.6)	165,693 (63.6)	164,642 (63.7)	193,916 (69.3)
Age group (years)				
15-24	128,975 (16.2)	43,751 (16.8)	30,033 (11.6)	55,191 (19.7)
25-34	170,243 (21.3)	55,092 (21.1)	52,864 (20.5)	62,287 (22.3)
35-54	376,073 (47.1)	123,957 (47.5)	130,796 (50.6)	121,320 (43.4)
> 55	123,540 (15.5)	37,930 (14.6)	44,686 (17.3)	40,924 (14.6)
Worker Experience				
Apprentice/trainee	18,094 (2.3)	8311 (3.2)	4915 (1.9)	4868 (1.7)
Other	698,155 (87.4)	251,901 (96.6)	253,023 (97.9)	193,231 (69.1)
Industry				
Agriculture, Forestry & Fishing	6597 (0.8)	2670 (1)	1463 (0.6)	2464 (0.9)
Mining	12,282 (1.5)	4103 (1.6)	787 (0.3)	7392 (2.6)
Manufacturing	144,065 (18)	45,428 (17.4)	41,619 (16.1)	57,018 (20.4)
Electricity, gas, water and waste services	8898 (1.1)	2895 (1.1)	2433 (0.9)	3570 (1.3)
Construction	82,741 (10.4)	23,867 (9.2)	23,868 (9.2)	35,006 (12.5)
Wholesale Trade	43,399 (5.4)	9752 (3.7)	18,913 (7.3)	14,734 (5.3)
Retail trade	79,132 (9.9)	20,408 (7.8)	29,100 (11.3)	29,624 (10.6)
Accommodation & Food Services	32,163 (4)	10,448 (4)	10,755 (4.2)	10,960 (3.9)
Transport, Postal & Warehousing	68,133 (8.5)	21,839 (8.4)	27,896 (10.8)	18,398 (6.6)
Information Media & Telecommunications	5612 (0.7)	1143 (0.4)	2910 (1.1)	1559 (0.6)
Financial & Insurance Services	5349 (0.7)	1272 (0.5)	2696 (1)	1381 (0.5)
Rental, Hiring & Real Estate Services	8751 (1.1)	2524 (1)	2827 (1.1)	3400 (1.2)
Professional, Scientific & Technical Services	15,455 (1.9)	3010 (1.2)	5799 (2.2)	6646 (2.4)
Administrative & Support Services	33,565 (4.2)	14,296 (5.5)	11,592 (4.5)	7677 (2.7)
Public Administration & Safety	51,829 (6.5)	23,291 (8.9)	15,589 (6)	12,949 (4.6)
Education & Training	57,344 (7.2)	25,769 (9.9)	12,825 (5)	18,750 (6.7)
Health Care & Social Assistance	101,627 (12.7)	38,318 (14.7)	31,857 (12.3)	31,452 (11.2)
Arts & Recreation Services	16,980 (2.1)	2453 (0.9)	7915 (3.1)	6612 (2.4)
Other Services	249,09 (3.1)	7244 (2.8)	7535 (2.9)	10,130 (3.6)
Claim severity				
Minor claims	346,512 (43.4)	95,215 (36.5)	66,800 (25.8)	184,497 (65.9)
Major claims	452,319 (56.6)	165,515 (63.5)	191,579 (74.1)	95,225 (34.0)

Table 2. The relative risks for workers' compensation claims in hot and cold temperatures stratified by worker, work and work environment characteristics in Brisbane and Perth, 2005-2016 (RR with 95% CI).

	Brisbane[a]				Perth[b]			
Exposure	**Extreme cold**	**Moderate cold**	**Moderate heat**	**Extreme heat**	**Extreme cold**	**Moderate cold**	**Moderate heat**	**Extreme heat**
Claim severity								
Minor claims	0.94 (0.80,1.10)	1.06 (0.97,1.17)	0.94 (0.88,1.01)	1.03 (0.86,1.22)	0.94 (0.84,1.05)	0.97 (0.91,1.03)	1.03 (0.97,1.10)	1.07 (0.96,1.20)
Major claims	0.87 (0.78,0.98)	0.96 (0.90,1.03)	0.97 (0.93,1.02)	0.96 (0.85,1.08)	1.01 (0.87,1.17)	1.04 (0.96,1.12)	0.90 (0.83,0.98)	0.92 (0.79,1.06)
Gender								
Male	0.89 (0.79-0.99)	0.99 (0.93,1.07)	0.97 (0.92,1.02)	1.01 (0.89,1.14)	0.95 (0.86,1.06)	0.98 (0.93,1.04)	1.01 (0.96,1.08)	1.07 (0.96,1.19)
Female	0.89 (0.77,1.05)	0.98 (0.90,1.08)	0.96 (0.90,1.02)	0.94 (0.80,1.11)	0.99 (0.85,1.16)	1.01 (0.93,1.10)	0.93 (0.85,1.02)	0.92 (0.79,1.07)
Age group (years)								
15-24	0.73 (0.58,0.92)	0.96 (0.84,1.10)	0.99 (0.90, 1.09)	1.16 (0.90,1.48)	0.98 (0.81,1.19)	1.01 (0.91,1.12)	1.03 (0.92,1.15)	1.15 (0.95,1.40)
25-34	0.84 (0.68,1.03)	1.01 (0.90,1.14)	0.95 (0.88 ,1.04)	1.05 (0.84,1.29)	0.91 (0.75,1.09)	0.97 (0.88,1.07)	0.92 (0.83,1.02)	0.91 (0.76,1.10)
35-54	0.95 (0.83,1.09)	1.01 (0.93 ,1.09)	0.97 (0.92 ,1.03)	0.99 (0.86,1.14)	0.93 (0.82,1.07)	0.98 (0.92,1.05)	0.97 (0.90,1.05)	1.03 (0.90,1.17)
>55	1.00 (0.78,1.28)	0.96 (0.83, 1.10)	0.93 (0.85 ,1.03)	0.74 (0.57,0.95)	1.15 (0.91,1.44)	1.03 (0.91,1.16)	1.09 (0.96,1.24)	0.98 (0.78,1.24)
Worker experience								
Apprentice/Trainee	0.76 (0.44,1.31)	1.05 (0.76,1.45)	0.88 (0.70,1.12)	0.96 (0.51,1.81)	0.64 (0.29,1.38)	0.85 (0.57,1.27)	0.79 (0.55,1.15)	0.85 (0.46,1.57)
Other	0.90 (0.82,0.99)	0.99 (0.94,1.05)	0.97 (0.93,1.01)	0.98 (0.89,1.09)	0.97 (0.87,1.08)	0.98 (0.93,1.04)	1.03 (0.97,1.09)	1.06 (0.96,1.18)
Potential workplace temperature exposure								
Regulated indoors	0.89 (0.79,0.99)	1.00 (0.93 , 1.07)	0.95 (0.91 ,1.01)	0.96 (0.85,1.09)	0.95 (0.85,1.05)	0.98 (0.93,1.04)	0.98 (0.92,1.04)	1.00 (0.90,1.11)
Unregulated indoors and outside	0.82 (0.38,1.76)	0.85 (0.54 ,1.33)	1.01 (0.73 ,1.38)	0.83 (0.36,1.93)	1.97 (0.87,4.47)	1.27 (0.82,1.98)	0.91 (0.58,1.43)	0.47 (0.22,1.03)
In a vehicle or cab	1.10 (0.76,1.58)	1.14 (0.92 ,1.41)	0.98 (0.85 ,1.14)	1.20 (0.81,1.75)	0.99 (0.68,1.43)	1.04 (0.85,1.27)	0.90 (0.73,1.11)	0.99 (0.68,1.43)
Multiple locations	0.85 (0.71,1.03)	0.95 (0.86 ,1.06)	0.98 (0.91 ,1.06)	1.00 (0.82,1.21)	0.96 (0.81,1.15)	0.99 (0.90,1.08)	1.04 (0.94,1.15)	1.13 (0.95,1.35)

Physical demands								
Limited (≤ 5kg)	0.78 (0.64,0.95)	0.91 (0.81,1.02)	0.97 (0.90,1.05)	0.91 (0.74,1.14)	0.96 (0.79,1.16)	1.00 (0.90,1.10)	1.00 (0.89,1.11)	1.07 (0.88,1.30)
Light (5-10kg)	1.05 (0.83,1.31)	1.16 (1.02,1.32)	0.88 (0.81,0.97)	0.94 (0.75,1.19)	0.96 (0.79,1.16)	0.99 (0.89,1.09)	1.01 (0.90,1.12)	1.06 (0.88,1.28)
Medium (10-20kg)	0.95 (0.81,1.12)	0.97 (0.89,1.07)	1.02 (0.95,1.08)	1.04 (0.87,1.22)	0.94 (0.82,1.09)	0.99 (0.92,1.07)	0.98 (0.90,1.06)	1.03 (0.90,1.19)
Heavy (>20 kg)	0.81 (0.67,0.97)	0.98 (0.88,1.10)	0.95 (0.89,1.03)	1.01 (0.83,1.23)	1.00 (0.83,1.20)	0.99 (0.89,1.09)	0.98 (0.89,1.09)	0.91 (0.76,1.10)
Industry								
Indoor	0.92 (0.71-1.20)	0.99 (0.94-1.06)	0.96 (0.92-0.99)	0.97 (0.73-1.28)	0.90 (0.82-1.00)	0.96 (0.91-1.01)	0.99 (0.93-1.05)	1.03 (0.93-1.14)
Outdoor	0.89 (0.81-0.98)	0.93 (0.80-1.09)	1.02 (0.91-1.13)	0.98 (0.88-1.09)	1.18 (0.98-1.41)	1.10 (0.99-1.21)	0.97 (0.87-1.07)	0.97 (0.81-1.16)

Abbreviations: CI confidence interval; RR, relative risk. *p <0.05

a. All temperatures were compared with the median maximum temperature of 27.0ºC.
b. All temperatures were compared with the median maximum temperature of 24.0ºC.

Table 3 The relative risks for workers' compensation claims in hot and cold temperatures using alternative temperature metrics in Brisbane, Melbourne and Perth, 2005-2016 (RR with 95% CI).

City	Brisbane		Melbourne		Perth	
Temperature metric	**Cold effect**	**Heat effect**	**Cold effect**	**Heat effect**	**Cold effect**	**Heat effect**
T_{max}*	0.89 (0.81-0.98)	0.98 (0.89-1.09)	0.99 (0.90-1.09)	1.14 (1.03-1.25)	0.96 (0.88-1.05)	1.02 (0.93-1.11)
T_{mean}	1.09 (0.97-1.21)	0.99 (0.90-1.09)	1.06 (0.96-1.16)	1.09 (0.99-1.19)	1.02 (0.93-1.12)	1.04 (0.94-1.14)
T_{min}	1.19 (1.08-1.30)	0.97 (0.88-1.07)	1.10 (1.01-1.20)	1.01 (0.92-1.10)	1.04 (0.95-1.14)	1.10 (0.99-1.21)
HX_{max}~	0.92 (0.84-1.01)	1.01 (0.91-1.10)	1.02 (0.93-1.12)	1.12 (1.02-1.24)	0.96 (0.89-1.05)	1.03 (0.94-1.14)
HI_{max}~	0.90 (0.82-0.99)	0.99 (0.90-1.09)	1.02 (0.93-1.12)	1.12 (1.02-1.24)	0.97 (0.89-1.06)	1.03 (0.93-1.14)
$WBGT_{max}$^	0.92 (0.85-1.02)	1.01 (0.92-1.11)	1.03 (0.94-1.13)	1.12 (1.02-1.24)	0.97 (0.89-1.06)	1.04 (0.94-1.14)
$UTCI_{max}$^	0.90 (0.83-0.99)	0.99 (0.90-1.11)	0.91 (0.84-1.01)	1.14 (1.03-1.26)	0.95 (0.88-1.04)	1.03 (0.93-1.13)
AT_{max}^	0.92 (0.84-1.02)	1.01 (0.91-1.11)	0.94 (0.86-1.03)	1.13 (1.03-1.24)	0.96 (0.88-1.05)	1.01 (0.92-1.11)

Abbreviations: Maximum humidex (HX_{max}); maximum heat index (HI_{max}); maximum wet-bulb globe temperature ($WBGT_{max}$); Universal Thermal comfort index ($UTCI_{max}$) and maximum apparent temperature (AT_{max})

Symbols used:

- Main metric used in this study*
- Composite temperature indices combining temperature and relative humidity ~
- Composite temperature indices combining temperature, relative humidity, wind speed and solar radiation ^