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The impact of sustained hot weather on risk of acute work-related injury in Melbourne, Australia

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Abstract It has been reported that weather-related high ambient temperature is associated with an increased risk of work-related injury. Understanding this relationship is important because work-related injuries are a major public health problem, and because projected climate changes will potentially expose workers to hot days, including consecutive hot days, more often. The aim of this study was to quantify the impact of exposure to sustained periods of hot weather on work-related injury risk for workers in Melbourne, Australia. A time-stratified case crossover study design was utilised to examine the association between two and three consecutive days and two and three consecutive nights of hot weather and the risk of work-related injury, using definitions of hot weather ranging from the 60th to the 95th percentile of daily maximum and minimum temperatures for the Melbourne metropolitan area, 2002–2012. Workers' compensation claim data was used to identify cases of acute work-related injury. Overall, two and three consecutive days of hot weather were associated with an increased risk of injury, with this effect becoming apparent at a daily maximum temperature of 27.6 °C (70th percentile). Three consecutive days of high but not extreme temperatures were associated with the strongest effect, with a 15% increased risk of injury (odds ratio 1.15, 95% confidence interval 1.01–1.30) observed when daily maximum temperature was ≥33.3 °C (90th percentile) for three consecutive days, compared to when it was not. At a threshold of 35.5 °C (95th percentile), there was no significant association between temperature and injury for either two or three consecutive days of heat. These findings suggest that warnings to minimise harm to workers from hot weather should be given, and prevention protocol initiated, when consecutive warm days of temperatures lower than extreme heat temperatures are forecast, and well before the upper ranges of ambient daytime temperatures are reached.

Keywords Work-related injury · High ambient temperature · Workers' compensation claims · Case crossover study · Occupational health

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Introduction

It has been reported that weather-related high ambient temperatures are associated with an increased risk of work-related injury (Adam-Poupart et al. 2015; McInnes et al. 2017; Morabito et al. 2006; Spector JT et al. 2016; Xiang et al. 2014b). This is important, not only because injuries acquired during the course of employment are a major public health concern both globally (International Labour Organisation 2016) and in Australia (Safe Work Australia 2015) but also because the climate is warming and will continue to do so into the future as human-generated greenhouse gases accumulate in the atmosphere (World Meteorological Organisation 2016).

For example, in Australia, mean surface temperatures have increased by 1 °C since 1910, and climate model projections indicate that this will continue to increase in the coming decades for all greenhouse gas emission scenarios. As mean

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temperatures increase, it is considered 'virtually certain' that hot and extremely hot days and warm nights will occur more frequently and 'very likely' that hot spells and heat waves will become more frequent, intense and longer lasting (Australian Bureau of Meteorology 2016b; IPCC 2013). These changes will potentially expose more workers to hot and extremely hot days, including consecutive hot days, more often.

Of the published studies that have investigated the association between ambient temperature and work-related injury, almost all have focused on the relationship between temperature on the day of injury and injury risk, rather than on the impact of consecutive hot days. One exception, set in Adelaide, found no significantly increased risk of injury overall as a consequence of exposure to consecutive days of extreme heat (i.e. heat waves, defined as ≥3 consecutive days of daily maximum temperature ≥35 °C or ≥5 consecutive days of ≥35 °C or ≥3 consecutive days of ≥40 °C daily maximum temperatures) when compared with non-heat wave periods (Xiang et al. 2014a). However, the null result in this investigation may be due to the relatively high threshold for excessive heat used in this study. It is possible that at extremely high temperatures, protective workplace practices are implemented, reducing injury risk. Findings from other studies examining contemporaneous effects of heat and work injury have also shown that the positive associations between daily temperature measures and injury risk diminish when extreme temperatures were reached (Spector JT et al. 2016; Xiang et al. 2014b). As a result, further examination of the relationship between consecutive days of high ambient temperature and work-related injury, where temperatures are high but less than extreme, is still needed.

A previous study set in Melbourne, Australia, found that daytime temperature was not associated with increased risk of injury overall (McInnes et al. 2017). This study did not examine the impact of consecutive hot days or thresholds for heat effects. The aim of this study is to address this research gap and to quantify the impact of exposure to sustained periods of hot weather on work-related injury risk for workers in Melbourne, Australia. Specifically, this study has examined the association between two and three consecutive days and two and three consecutive nights of hot weather and risk of work-related injury.

Materials and methods

Approach and setting

A case crossover study design, utilising a time-stratified approach to referent selection, was employed to investigate the impact of sustained periods of hot weather on risk of work-related injury to workers in Melbourne, Australia, 2002–2012 (Janes et al. 2005; Maclure 1991). Workers' compensation claim administrative data was used to identify cases of acute work-related injury.

With a population of approximately 4.5 million (at 2015), Melbourne is the second most populous city in Australia (Australian Bureau of Statistics 2016a). A mid-latitude city, Melbourne, has a temperate climate characterised by changeable weather conditions (Australian Bureau of Meteorology 2016a; Nicholls et al. 2008). The Melbourne metropolitan area, covering an area of approximately 8500 km^2, includes a central business district and suburban surrounds, and is divided into 31 geographical areas of local government responsibility, referred to as local government areas (LGAs) (Australian Bureau of Statistics 2016b).

Outcome data

De-identified workers' compensation claim administrative data was used to identify cases of work-related injury. These data were obtained, on application, from the Compensation Research Database (CRD), a repository of workers' compensation claims made to WorkSafe Victoria, the statutory body responsible for managing the Victorian workers' compensation scheme WorkCover, with which an estimated 85% of all Victorian workers are insured (Prang et al. 2016). A case of acute work-related injury was defined as a standard accepted worker's compensation claim for an episode of non-fatal or fatal acute injury to a worker aged 15 years or over, inflicted at a workplace located in the Melbourne metropolitan area, during the months of November to March (inclusive) over the period of 1 July 2002 to 30 June 2012. A standard claim in Victoria is defined as one where there has been at least a 10-day absence from work as a consequence of the injury, or where the incurred health care expenses exceed a specified threshold. Injuries acquired on the journey to or from work are not compensable with the WorkCover scheme (WorkSafe Victoria 2012). The 5 months, November to March, were chosen for analysis as they are the warmest months of the year in Melbourne.

Guided by the definition of acute injury as one resulting from acute exposure to intolerable levels of energy, or lack or a vital element such as oxygen, with this damage being quickly apparent (Holder et al. 2001), claims for acute injuries were selected from the dataset using nature of injury information coded according to the Nature of Injury/Disease Classification System for Victoria (VCODE) (Victorian Workcover Authority 2008). The acute injuries most frequently represented in the dataset were those categorised as 'contusion, bruising, crushing and traumatic soft tissue injury'(14.5%) and 'other fractures, not classified elsewhere' (14.2%). Claims for non-acute injuries were excluded from the study if they were listed in VCODE categories describing disorders and diseases most likely resulting from repeated or long-term occupational exposures. The most frequently excluded non-acute injuries were 'back pain, strain (non-traumatic), lumbago and sciatica' (31.3%), other reactions to stressors (16.2%) and 'muscle strain (non-traumatic)' (9.1%). A list of the most frequently included acute injuries and excluded non-acute injuries can be found in Appendix 1.

Administrative data describing a total of 547,287 worker's compensation claims was received from the CRD. After exclusion of 228,684 minor claims (injury claims for which the number of days of work absence and associated costs are not expected to satisfy threshold criteria, and for which reporting obligations differ from those of standard claims), and 156,148 claims for non-acute injuries, a total of 162,455 claims remained, of which 65,487 were for injuries that occurred during the months November to March 2002–2012 (see flowchart describing claim selection in Appendix 2). Information available with each workers' compensation claim included the date of injury, the LGA of the workplace where the injury was sustained, the LGA of the claimant's residence, the industry of employment, occupational group, type of injury and the sex and age of the claimant.

Exposure data

Meteorological data for the Melbourne metropolitan area was obtained from the Australian Government Bureau of Meteorology. Data was received from a total of 16 weather stations, from which 8 with the most complete weather records over the study period were selected. The approximate location of these weather stations within the Melbourne metropolitan area is illustrated in Fig. 1.

Data from these 8 weather stations was assigned to the 31 LGAs, with each LGA allocated data from the weather station that was closest to the most densely populated area of that LGA, or in the case of inner city areas, to the centre of that LGA. In this way, each LGA was allocated the data from one weather station only. The most recently available census data and a geospatial mapping tool provided on the Victorian government website were used to estimate populations and distances (Australian Bureau of Statistics 2013; State Government of Victoria 2016).

The temperature measures 'daily maximum temperature' (maximum temperature in the 24 h after 09.00 h) and 'daily minimum temperature' (minimum temperature in the 24 h before 09.00 h) were chosen to investigate the relationship between sustained hot days and hot nights, and work-related injury. Whilst use of a heat index such as apparent temperature (AT) may have provided a more accurate indication of heat stress, we did not have access to solar radiation data, so any calculation of AT would have been an approximation (Australian Bureau of Meteorology 2010). In addition, in Melbourne, the term AT is not one in popular use, limiting its usefulness for policy translation (e.g. for warnings, activation of heat plans). Daily maximum and minimum

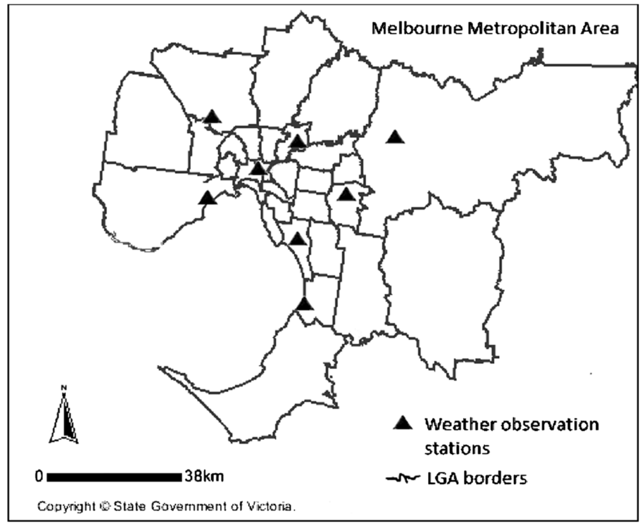

Fig. 1 Melbourne metropolitan area showing the local government area (LGA) borders and the location of weather observation stations from which exposure data was sourced

temperatures, on the other hand, are very accessible to workers as they are reported in daily weather forecasts of the Melbourne Office of the Australian Bureau of Meteorology. Relative humidity (RH) data was also extracted as this is a likely confounder of the ambient temperature–work-related injury relationship, influencing the effectiveness of thermoregulation through evaporative heat loss (Parsons 2003). RH data for each day was extracted for 15.00 and 06.00 h as daily maximum and minimum temperatures are typically reached in Melbourne between 14.00–15.00 h and 05.00–06.00 h, respectively (Australian Bureau of Meteorology 2010; Nicholls et al. 2008). Meteorological data was merged with compensation data according to injury date.

Analysis

Using a time-stratified case crossover study design, a case day was defined as a day on which an acute injury had occurred, and referent days were selected to match each case by day of the week, calendar month and year (Janes et al. 2005). In this way, known and unknown time-independent, individual-level confounders (such as smoking status, chronic disease) and other time-dependent confounders (day of the week, season, year) were controlled by design.

In the absence of definitions for a hot day or a hot night for the Melbourne metropolitan area, a range of relative measures were chosen *a priori* by defining hot weather as being greater than or equal to the 60th, 65th, 70th, 75th, 80th, 85th, 90th and 95th percentiles for mean daily maximum and mean daily minimum temperatures recorded by the eight weather observation stations during the study period. For each of these temperature thresholds, exposures on case days were compared with exposures on referent days, using conditional logistic regression models, to determine if days with daily maximum or daily minimum temperatures above a particular threshold, that were also preceded by one (i.e. two consecutive hot days/hot nights) or two (i.e. three consecutive hot days/hot nights) days above the same threshold, were associated with a higher probability of falling on a case day, compared to referent days. In this way, separate models were used to assess the odds ratios of injury occurring when exposed to each of two hot days, three hot days, two hot nights and three hot nights, when compared to not being exposed to this. Case days and referent days with missing meteorological data were removed, as were case days and associated referent days that fell on public holidays.

To assess potential vulnerability of demographic and occupational subgroups to sustained hot weather, we also ran additional models stratified by sex (male/female), age group (<34, 35–49 and ≥55 years) and an occupational subgrouping characterising potential exposure to outdoor temperatures. We classified occupations into five different exposure classification groups, using the Australian and New Zealand Standard Classification of Occupations (ANZCO) code associated with each claimant. The five categories used were (1) working in a vehicle or cab only, (2) working outdoors with no work in regulated indoor climate, (3) working in a regulated indoor climate, (4) working in an unregulated indoor climate and working in vehicle or cab and (5) working in indoor and outdoor environments. The system used to assign the ANZCO codes to each categories has previously been described, and the validity of using this categorisation system with Victorian workers' compensation claim data has been demonstrated (Government of Canada 2011; McInnes et al. 2017; Smith and Berecki-Gisolf 2014).

Results are presented as odds ratios (ORs) and 95% confidence intervals (CIs), and represent the odds of acute work-related injury occurring when a worker is exposed to consecutive days of hot weather compared to not being exposed to this. All analyses were conducted using Stata v.12 (Stata 12.1.2011, StataCorp, College Station LP, TX, USA). P values of <0.05 were considered to be statistically significant.

Ethics

The Monash University Human Research Ethics Committee granted this study exemption from ethics review on 13 December 2012, as only non-identifiable data was to be used.

Results

There were 65,487 workers' compensation claims that met the study inclusion criteria. Of these claims, a total of 1547 claims for injury had occurred on public holidays and were removed as work environment characteristics such as staffing levels and workloads are likely to be different to those of usual working days. A further 5369 claims that had missing residential or workplace-level temperature or humidity data on either the day of the injury or the 2 days prior were also removed, leaving a sample of 58,571 claims. The dates of injury described in these claims became the case days, and were matched with 181,628 referent days. Of this final sample, 38 case days could not be matched with any referent days and were removed leaving a final sample of 58,533 case days and 181,628 referent days. Restriction to case days that occurred in the Melbourne metropolitan area left 46,288 case days and 144,340 referent days, a final total of 190,628 observations (see Appendix 2). Of the 46,288 cases of injury, a majority were of male workers (72%), and were aged 35–49 years (37%).

Mean daily meteorological data, as recorded by the eight weather observation stations located in the Melbourne metropolitan area, is presented in Table 1 as percentiles, for the months of November to March, 2002–2012. The number and percentage of days satisfying the criteria for two or three hot days and two or three hot nights at each threshold during the study period is provided in Table 2. It can be seen that there is an overall trend for an increasing number of 2- and 3-day hot spells over the study period for most temperature thresholds, with only three consecutive hot nights ≥85th temperature percentile showing a negative change.

Table 3 shows an increased risk of injury associated with both two and three consecutive days of hot weather exposure, when compared to not being exposed to this, which was statistically significant for the 70th, 75th, 80th, 85th and 90th temperature percentiles. This effect on injury risk of an increasing number of days of exposure displayed a dose-response relationship, with higher risks observed for 3-day exposure than for 2-day exposure for all temperature thresholds. For both two and three consecutive hot days, the odds of injury became statistically significant at the 70th percentile of mean maximum temperature, which is equivalent to 27.6 °C in Melbourne. When compared with not being exposed, two consecutive days of daily maximum temperature ≥27.6 °C was associated with a 4% (OR 1.042, 95% CI 1.009–1.077) increased odds of injury, and 5% (OR 1.047, 95% CI 1.004–1.093) increased odds of injury for three consecutive hot days. For both two and three consecutive hot days, the odds of injury was found to increase with increasing temperature percentiles, up to the 90th percentile. For two consecutive hot days, the odds of injury reached 7% at the 80th temperature percentile, and remained the same to the 90th percentile. For 3-day exposure, the odds of injury continued to rise to a maximum of 15% (OR 1.15, 95% CI 1.01–1.30) for the 90th temperature percentile (33.3 °C). At the 95th percentile (35.5 °C), the association between temperature and injury become insignificant for both two and three consecutive days of heat. Table 3 also shows the results of assessment of injury

Table 1 Mean daily meteorological data recorded by eight weather observation stations located in the Melbourne metropolitan area, Victoria, 2002 to 2012 (November–March inclusive), presented as percentiles

Meteorological variables	Percentiles									
	25%	50%	60%	65%	70%	75%	80%	85%	90%	95%	IQR[a]
Maximum daily temperature (°C)	20.8	24	25.6	26.5	27.6	28.8	30.2	31.7	33.3	35.5	8.0
Minimum daily temperature (°C)	11.2	13.4	14.2	14.7	15.1	15.7	16.3	17	18	19.5	4.5
Relative humidity at 15.00 h (%)	38	49	53	55	57	59	62.0	66	71	79	21.0
Relative humidity at 06.00 h (%)	71	82	85	87	89	90	92.0	93	95	97	19.0

[a] Interquartile range = difference between 75th and 25th percentile of measured exposure

odds on days preceded by two and three consecutive nights of hot weather, compared to not being exposed to this. Unlike hot days, no consistent pattern was observed for hot nights, either with increasing levels of the temperature threshold, or between two and three hot nights of exposure.

A series of subgroup analyses also examined the relationship between sustained days and nights of heat exposure and risk of injury for men and women, and by different age groups (<35, 35 to 49, 50+ years), and by different occupational environmental exposure groups. Given that no relationship was observed for consecutive hot nights and risk of work injury, these analyses are only presented for hot days. As shown in Table 4, the relationship between two and three hot days and injury was more pronounced amongst men than women at each temperature threshold. Amongst age groups, the relationship between hot days and injury risk was more pronounced amongst younger age groups (<35 years) at lower thresholds (70th to 80th percentile), but more pronounced amongst the middle age groups (35–49 years) at higher thresholds (80th to 90th percentile). Tables A3-1 and A3-2 in Appendix 3 show the results of subgroup analysis according to occupational environmental exposure group. It can be seen that there was no increased risk of injury associated with the occupational group ‘outdoors with no work in regulated indoor climate’, with odds ratios for this group consistently at or slightly below 1. Statistically significant associations were seen for 2-day temperature thresholds and injury for the occupational group ‘working in regulated indoor climate’, with a stronger effect observed for 3 days of sustained temperatures at the 80th and 85th temperature thresholds. Significantly increased odds of injury were also observed for the occupational group ‘working only in vehicle or cab’ when 3 days of sustained temperatures reached the 70th and 75th temperature thresholds.

Discussion

This study has examined the relationship between consecutive days and nights of hot weather and risk of work-related injury. Understanding this relationship is important in light of climate change projections and the impact of work-related injuries at the human and economic scale. We found that two and three consecutive days of hot weather were associated with an increased risk of injury, and that this effect became apparent at a relatively low daily maximum temperature of 27.6 °C, equivalent to the 70th percentile of maximum temperature distributions for Melbourne during the study period. The odds of injury were found to increase with increasing temperature percentiles, up to the 90th percentile, with higher risks associated with 3- than 2-day exposure for all temperature thresholds. Three consecutive days of hot weather defined by high but not extremely high temperatures were associated with the strongest effect, with a 15% increased risk of injury (OR 1.15, 95% CI 1.01–1.30) observed when daily maximum temperature was ≥33.3 °C (90th percentile) for three consecutive days, compared to when it was not. We found no significant association between temperature and injury for either two or three consecutive hot days at the 95th percentile threshold of daily maximum temperature (35.5 °C). On stratification for age group, the risk of work-related injury with two hot days was found to be greatest for the middle age group (35–49 years) at the higher-temperature thresholds, whilst this pattern was less consistent for three hot days. No excess risk associated with primarily outdoor occupations was evident on stratification of claimant’s occupations according to environmental exposure group.

These findings are new. While Xiang et al. (2014b) have investigated the impact of heat waves (consecutive days of extreme heat), other studies located in the literature have focused on the relationship between temperature on the day of injury and injury risk, rather than on the impact of consecutive hot days. The effects we have observed are likely to be due to cumulative effects of consecutive hot days, rather than the independent effects of three individual days of heat, as previous analyses of the same study data found no relationship between daytime temperature and risk of injury on the same day (McInnes et al. 2017). Our findings suggest that magnitude of temperature and duration of exposure are important factors influencing injury risk up to a certain point.

The mechanism behind these effects is not clear. Physical and behavioural factors such as slippery sweaty hands, hot tools and working faster to avoid the heat of the day may have

Table 2 Number and percentage of days, November to March (inclusive), 1 July 2002–30 June 2012, satisfying the criteria of two or three consecutive hot days, and two or three consecutive hot nights at thresholds defined by the 60th–95th percentile temperatures, using mean data from all eight weather stations combined

Temperature percentiles	60%		65%		70%		75%		80%		85%		90%		95%	
Year	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Two hot days																
2002–2003	31.5	(20.9%)	26.5	(17.6%)	21.5	(14.3%)	17.1	(11.4%)	11.1	(7.4%)	8.3	(5.5%)	3.6	(2.4%)	0.9	(0.6%)
2003–2004	27.5	(18.2%)	22.4	(14.8%)	18.6	(12.3%)	14.8	(9.7%)	10.9	(7.2%)	5.4	(3.5%)	2.5	(1.7%)	0.6	(0.4%)
2004–2005	28.6	(19.0%)	20.3	(13.4%)	12.9	(8.5%)	9.4	(6.2%)	6.9	(4.6%)	4.8	(3.2%)	1.9	(1.2%)	0.1	(0.1%)
2005–2006	37.1	(24.6%)	29.5	(19.5%)	22.6	(15.0%)	18.4	(12.2%)	14.4	(9.5%)	9.8	(6.5%)	6.5	(4.3%)	3.8	(2.5%)
2006–2007	45.8	(30.7%)	38.6	(25.9%)	31.6	(21.2%)	23.9	(16.0%)	18.3	(12.2%)	14.0	(9.4%)	8.3	(5.5%)	3.1	(2.1%)
2007–2008	47.3	(31.1%)	38.5	(25.3%)	31.0	(20.4%)	24.9	(16.4%)	17.1	(11.3%)	12.5	(8.2%)	8.8	(5.8%)	5.3	(3.5%)
2008–2009	38.5	(25.5%)	33.8	(22.4%)	27.6	(18.3%)	20.6	(13.7%)	12.8	(8.4%)	9.5	(6.3%)	6.5	(4.3%)	3.6	(2.4%)
2009–2010	49.9	(33.0%)	43.3	(28.6%)	34.4	(22.8%)	26.9	(17.8%)	20.8	(13.7%)	15.1	(10.0%)	9.0	(6.0%)	3.4	(2.2%)
2010–2011	33.5	(22.2%)	24.6	(16.3%)	15.9	(10.5%)	10.8	(7.1%)	6.0	(4.0%)	2.9	(1.9%)	1.6	(1.1%)	0.9	(0.6%)
2011–2012	40.5	(26.6%)	32.8	(21.5%)	24.3	(16.0%)	18.0	(11.8%)	12.4	(8.1%)	8.5	(5.6%)	4.5	(3.0%)	1.0	(0.7%)
Percent change 2002/2012	28.6%		23.6%		12.8%		5.1%		11.2%		3.0%		24.1%		14.3%	
Three hot days																
2002–2003	15.4	(10.2%)	11.9	(7.9%)	8.5	(5.7%)	6.5	(4.3%)	3.3	(2.2%)	1.8	(1.2%)	0.0	(0.0%)	0.0	(0.0%)
2003–2004	13.8	(9.1%)	10.1	(6.7%)	7.8	(5.1%)	5.6	(3.7%)	2.9	(1.9%)	0.9	(0.6%)	0.0	(0.0%)	0.0	(0.0%)
2004–2005	14.5	(9.6%)	9.3	(6.1%)	4.8	(3.2%)	2.4	(1.6%)	0.9	(0.6%)	0.3	(0.2%)	0.0	(0.0%)	0.0	(0.0%)
2005–2006	21.6	(14.3%)	16.4	(10.8%)	11.1	(7.4%)	9.0	(6.0%)	7.1	(4.7%)	4.3	(2.8%)	2.6	(1.7%)	0.8	(0.5%)
2006–2007	28.4	(19.0%)	23.0	(15.4%)	18.1	(12.1%)	11.8	(7.9%)	7.8	(5.2%)	5.8	(3.9%)	2.9	(1.9%)	1.0	(0.7%)
2007–2008	31.1	(20.5%)	24.1	(15.9%)	17.5	(11.5%)	13.9	(9.1%)	7.9	(5.2%)	4.5	(3.0%)	1.8	(1.2%)	1.1	(0.7%)
2008–2009	24.3	(16.1%)	21.1	(14.0%)	16.9	(11.2%)	11.8	(7.8%)	6.1	(4.1%)	4.6	(3.1%)	2.9	(1.9%)	1.8	(1.2%)
2009–2010	32.3	(21.4%)	27.1	(18.0%)	19.6	(13.0%)	15.1	(10.0%)	11.0	(7.3%)	7.0	(4.6%)	2.9	(1.9%)	0.3	(0.2%)
2010–2011	20.9	(13.8%)	13.0	(8.6%)	6.9	(4.6%)	4.5	(3.0%)	2.4	(1.6%)	1.3	(0.8%)	0.6	(0.4%)	0.4	(0.2%)
2011–2012	22.3	(14.6%)	16.4	(10.8%)	11.5	(7.6%)	8.3	(5.4%)	4.9	(3.2%)	2.9	(1.9%)	1.0	(0.7%)	0.0	(0.0%)
Percent change 2002/2012	44.7%		37.9%		35.3%		26.9%		50.0%		64%		–		–	
Two hot nights																
2002–2003	34.0	22.7%	28.4	18.9%	21.1	14.1%	16.8	11.2%	11.6	7.8%	8.3	5.5%	4.5	3.0%	2.0	1.3%
2003–2004	21.6	14.3%	15.8	10.4%	11.4	7.5%	7.0	4.6%	4.3	2.8%	2.6	1.7%	1.0	0.7%	0.1	0.1%
2004–2005	25.6	17.0%	20.0	13.3%	16.3	10.8%	12.1	8.0%	8.8	5.8%	4.8	3.2%	2.8	1.8%	1.0	0.7%
2005–2006	37.0	24.5%	30.9	20.4%	27.1	18.0%	19.6	13.0%	14.1	9.4%	8.9	5.9%	5.5	3.6%	1.5	1.0%
2006–2007	44.5	29.8%	36.5	24.5%	32.6	21.9%	28.4	19.0%	23.6	15.8%	17.4	11.6%	10.5	7.0%	4.5	3.0%
2007–2008	47.6	31.3%	40.5	26.6%	34.5	22.7%	24.8	16.3%	17.4	11.4%	12.5	8.2%	5.5	3.6%	1.6	1.1%
2008–2009	27.9	18.5%	20.9	13.8%	17.1	11.3%	14.5	9.6%	10.1	6.7%	7.6	5.0%	5.1	3.4%	2.5	1.7%
2009–2010	54.5	36.1%	46.5	30.8%	40.4	26.7%	30.4	20.1%	22.3	14.7%	16.3	10.8%	9.0	6.0%	2.5	1.7%

Table 2 (continued)

Temperature percentiles																
2010–2011	46.4	30.8%	37.9	25.2%	33.3	22.1%	27.1	18.0%	20.0	13.3%	15.6	10.4%	8.9	5.9%	2.9	1.9%
2011–2012	44.1	29.0%	36.0	23.7%	28.9	19.0%	23.1	15.2%	16.0	10.5%	10.3	6.7%	5.8	3.8%	2.0	1.3%
Percent change 2002/2012	29.8%		26.9%		36.7%		38.1%		37.6%		24.2%		27.8%		0.0%	
Three hot nights																
2002–2003	21.8	14.5%	17.3	11.5%	12.3	8.2%	8.6	5.8%	5.5	3.7%	3.5	2.3%	1.0	0.7%	0.1	0.1%
2003–2004	11.3	7.4%	7.4	4.9%	4.6	3.1%	2.5	1.7%	0.9	0.6%	0.4	0.2%	0.1	0.1%	0.0	0.0%
2004–2005	16.4	10.9%	11.9	7.9%	9.0	6.0%	6.8	4.5%	4.9	3.2%	2.6	1.7%	1.6	1.1%	0.5	0.3%
2005–2006	24.1	16.0%	18.5	12.3%	16.3	10.8%	10.6	7.0%	7.0	4.6%	3.9	2.6%	2.6	1.7%	0.8	0.5%
2006–2007	35.1	23.5%	28.1	18.8%	25.0	16.8%	21.1	14.2%	17.5	11.7%	12.5	8.4%	7.0	4.7%	2.5	1.7%
2007–2008	34.3	22.5%	28.0	18.4%	21.8	14.3%	13.5	8.9%	8.1	5.3%	5.4	3.5%	1.8	1.2%	0.1	0.1%
2008–2009	18.4	12.2%	14.4	9.5%	12.5	8.3%	10.9	7.2%	7.4	4.9%	5.3	3.5%	4.0	2.6%	1.5	1.0%
2009–2010	39.5	26.2%	32.9	21.8%	27.0	17.9%	18.4	12.2%	12.5	8.3%	9.0	6.0%	3.6	2.4%	0.6	0.4%
2010–2011	35.1	23.3%	28.0	18.6%	24.3	16.1%	19.4	12.9%	13.6	9.1%	9.6	6.4%	5.1	3.4%	1.1	0.7%
2011–2012	29.5	19.4%	22.9	15.0%	16.6	10.9%	12.3	8.1%	7.1	4.7%	3.1	2.1%	1.1	0.7%	0.1	0.1%
Percent change 2002/2012	35.6%	32.6%	35.7%	42.0%	29.5%	−10.7%	12.5%	0.0%								

acute impacts on injury risk, but it could be speculated that more sustained effects of heat are related to a combination of these physical issues with other factors such as fatigue, lack of sleep and irritability. Sleep disturbance is reported to have been a predictor of occupational injuries for a cohort of public sector employees (Salminen et al. 2010). The impacts of heat on older people have been well documented at the population level, with a combination of factors including reduced thermoregulatory capacity, and chronic illness reported to increase risk of harm for people aged ≥65 years (Kenny et al. 2010). However, there has been little investigation of the impacts of heat on older workers. Further assessment of the impact of hot weather, including consecutive days of hot weather on older workers, is warranted in light of an ageing workforce (Productivity Commission 2013). Our observation of no excess risk of injury associated with outdoor work is in agreement with previous assessments of association with single hot days, using the Victorian workers' compensation data, and may be due to better acclimatisation of outdoor workers to hot weather, greater awareness of the impacts of heat, or because outdoor work itself is not the primary occupational exposure associated with increased risk of injury on hotter days. For example, stronger associations between daily temperature and heat have previously been found amongst workers with higher physical demand requirements (McInnes et al. 2017). Conversely, our observation of increased risk of injury for workers in regulated indoor environments may reflect reduced opportunity for acclimatisation, and limited awareness of the health impacts of hot weather. At extreme temperatures (≥35.5), risk of injury diminished for both two and three hot days. Understanding the mechanism underlying this observation warrants further investigation, as any behavioural or workplace practice changes that are being adopted at extreme temperatures may inform effective adaptation strategies in the future.

This study has a number of strengths. The case crossover design we have employed, regarded as appropriate for an investigation of association between transient exposure and abrupt outcome, not only facilitates control for known and unknown time-invariant, individual-level confounders by having each subject serve as their own control but also provides a relatively straightforward method to control for the confounding effects of day of the week and month, which are important in an occupational setting (Maclure and Mittleman 2000). Rather than using only one centrally located weather station, exposure data has been sourced from eight weather stations located throughout the Melbourne metropolitan area, and matched to cases aggregated to LGAs according to weather station proximity to the most densely populated areas of that LGA, minimising exposure misclassification. Finally, as there are no working definitions of hot weather for Melbourne, we explored a variety of definitions of a hot day. Population-level studies of the health impacts of heat

Table 3 Odds ratios (ORs) for associations between two and three hot days, two and three hot nights, and acute work-related injury, with hot days and nights defined as the ≥60th–95th percentiles of maximum and minimum daily temperatures in metropolitan Melbourne, November to March, 2002–2012

Exposures	Two hot days			Three hot days		
Temperature percentile (maximum daily temperature, °C)	Cases (*n*)	OR	95% CI	Cases (*n*)	OR	95% CI
60th (25.6)	11,356	1.03	1.00–1.06	6,528	1.03	1.00–1.07
65th (26.5)	9,166	1.02	0.99–1.05	5,037	1.03	1.00–1.07
70th (27.6)	7,111	1.04	1.01–1.08	3,509	1.05	1.00–1.09
75th (28.8)	5,439	1.06	1.02–1.10	2,445	1.07	1.02–1.13
80th (30.2)	3,911	1.07	1.03–1.12	1,554	1.09	1.02–1.16
85th (31.7)	2,780	1.07	1.02–1.12	987	1.11	1.03–1.19
90th (33.3)	1,548	1.07	1.00–1.14	340	1.15	1.01–1.30
95th (35.5)	563	1.07	0.97–1.18	108	1.09	0.87–1.36
	Two hot nights			Three hot nights		
Temperature percentile (minimum daily temperature, °C)	Cases (*n*)	OR	95% CI	Cases (*n*)	OR	95% CI
60 (14.2)	12,666	1.03	1.01–1.06	8,859	1.02	0.99–1.05
65 (14.7)	10,309	1.02	1.0–1.05	6,919	1.01	0.98–1.04
70 (15.1)	8,628	1.01	0.99–1.04	5,603	1.01	0.98–1.04
75 (15.7)	6,776	1.02	0.99–1.06	4,208	1.03	0.99–1.07
80 (16.3)	4,998	1.04	1.00–1.08	2,902	1.03	0.98–1.08
85 (17.0)	3,494	1.03	0.99–1.08	1,904	1.04	0.98–1.09
90 (18.0)	1,981	1.04	0.98–1.10	964	1.06	0.98–1.14
95 (19.5)	685	1.06	0.97–1.16	261	1.09	0.94–1.25

OR odds ratio, *CI* confidence interval

have reported that effects vary geographically, likely reflecting the acclimatisation, sensitivity and adaptive capacity of exposed communities (Hajat and Kosatky 2010). For this reason, we chose a relative approach to defining hot weather in Melbourne, using temperature percentiles for the Melbourne metropolitan area, over the study period. The 95th maximum daily temperature percentile has been identified in other settings as representing extreme heat (Tobías et al. 2010), but as discussed, there is evidence to suggest that impacts of hot weather in an occupational setting may not be evident at extreme temperatures (Morabito et al. 2006; Spector JT et al. 2016; Xiang et al. 2014b). Therefore, we chose *a priori* to define hot weather according to a range of percentile values, ranging from the 60th to the 95th temperature percentiles. By using relative temperature thresholds, our findings may be generalisable to other mid-latitude temperate climate settings.

Our results should be interpreted given the following limitations. Although we have utilised meteorological data from eight weather observation stations to estimate case exposures in the Melbourne metropolitan area, the study is still subject to exposure misclassification as we do not have information about actual workplace or residential temperatures to which cases were exposed. In addition, information about access to air conditioning either in the workplace or in the place of residence was not available to us. Percentile temperatures have been estimated using mean data from the eight weather stations, whereas temperatures assigned to cases within LGAs are from individual weather stations. Also, the eight selected weather stations are not evenly distributed around the Melbourne metropolitan area. Use of compensation claim data as a source of work-related injury is likely to underestimate the number of injury cases, as not all workers eligible for compensation will submit a claim, and not all claims for injury will be eligible for compensation. A survey of Australian workers conducted in 2009/2010 found that of those who had been injured in the previous 12 months, 57% did not apply for compensation, with 33% explaining that they thought the injury was too minor or it required too much effort to make a claim, and 10% not knowing they were insured (Safe Work Australia 2011). A study comparing sources of work-related injury data in Victoria has reported that hospital emergency department data captured a greater proportion of injuries to young workers than compensation claim data (McInnes et al. 2014). In addition, since injury cases represented in the compensation claims are those that have required at least 10 days absence from work, or have incurred minimum costs to be compensated by WorkSafe Victoria, they are likely to represent only the most serious injuries. Finally, whilst the case crossover study design has a number of advantages, it also has some limitations. The design assumes that over the study period, there are no time trends in exposures (Janes et al. 2005). We addressed this potential limitation by restricting analysis to the hottest months of the year. In addition, any potential individual-level confounders that arise for just a

Table 4 Odds ratios (ORs) for association between exposure to two and three hot days, and acute work-related injury, with hot days and nights defined as the ≥60th–95th percentiles of maximum daily temperature in the Melbourne metropolitan area, during the months November–March (inclusive), 2002–2012, according to gender and age group

		Two hot days			Three hot days		
Temperature percentile (°C)		Cases (*n*)	OR	95% CI	Cases (*n*)	OR	95% CI
60th (25.6 °C)							
Gender	Male	8167	1.03	1.00–1.07	4670	1.04	1.00–1.08
	Female	3189	1.01	0.96–1.06	1858	1.02	0.96–1.09
Age group	<35	3867	1.05	1.00–1.10	2197	1.04	0.98–1.10
	35–49	4210	1.01	0.96–1.05	2396	1.02	0.97–1.08
	50+	3279	1.02	0.97–1.08	1935	1.04	0.98–1.10
65th (26.5 °C)							
Gender	Male	6593	1.03	0.99–1.07	3596	1.03	0.99–1.08
	Female	2573	1.01	0.95–1.07	1441	1.04	0.97–1.11
Age group	<35	3128	1.06	1.01–1.12	1697	1.05	0.99–1.12
	35–49	3429	1.01	0.96–1.06	1882	1.04	0.98–1.10
	50+	2609	1.00	0.95–1.06	1458	1.01	0.95–1.08
70th (27.6 °C)							
Gender	Male	5127	1.05	1.01–1.10	2503	1.05	1.00–1.10
	Female	1984	1.01	0.95–1.08	1006	1.04	0.96–1.13
Age group	<35	2445	1.09	1.03–1.15	1185	1.07	0.99–1.15
	35–49	2668	1.03	0.98–1.09	1303	1.05	0.98–1.12
	50+	1998	1.01	0.95–1.07	1021	1.03	0.95–1.11
75th (28.8 °C)							
Gender	Male	3936	1.07	1.03–1.12	1760	1.09	1.02–1.15
	Female	1503	1.03	0.96–1.10	685	1.04	0.95–1.14
Age group	<35	1865	1.09	1.02–1.16	821	1.09	0.99–1.18
	35–49	2028	1.04	0.98–1.10	900	1.05	0.96–1.14
	50+	1546	1.06	0.99–1.13	724	1.10	1.00–1.20
80th (30.2 °C)							
Gender	Male	2821	1.08	1.03–1.14	1122	1.10	1.02–1.18
	Female	1090	1.06	0.98–1.15	432	1.06	0.94–1.19
Age group	<35	1324	1.07	1.00–1.15	513	1.06	0.95–1.18
	35–49	1501	1.10	1.03–1.17	583	1.10	1.00–1.22
	50+	1086	1.05	0.97–1.13	458	1.10	0.98–1.23
85th (31.7 °C)							
Gender	Male	2007	1.07	1.01–1.13	709	1.10	1.02–1.18
	Female	773	1.07	0.97–1.17	278	1.15	1.00–1.33
Age group	<35	918	1.04	0.95–1.13	316	1.04	0.91–1.19
	35–49	1100	1.13	1.04–1.22	388	1.15	1.02–1.30
	50+	762	1.03	0.94–1.12	283	1.13	0.98–1.30
90th (33.3 °C)							
Gender	Male	1127	1.08	1.01–1.17	251	1.03	1.03–1.39
	Female	421	1.03	0.92–1.16	89	0.80	0.80–1.30
Age group	<35	517	1.08	0.97–1.20	108	0.85	0.85–1.33
	35–49	625	1.13	1.03–1.25	137	0.98	0.98–1.47
	50+	406	0.98	0.87–1.10	95	0.91	0.91–1.48
95th (35.5 °C)							
Gender	Male	416	1.11	0.99–1.25	79	1.17	0.90–1.51
	Female	147	0.95	0.79–1.15	29	0.93	0.61–1.42
Age group	<35	179	1.04	0.88–1.24	32	0.97	0.65–1.45
	35–49	241	1.21	1.04–1.41	52	1.28	0.93–1.78
	50+	143	0.91	0.75–1.10	107	0.94	0.59–1.48

short period of time, such as unusual clothing or physical load requirements, will not be controlled for using this approach (Checkoway et al. 2007).

The findings from this study have important occupational health and safety (OH&S) implications. There are no current WorkSafe Victoria guidelines or regulations suggesting a threshold at which extra precautions should be taken to guard against injury whilst working in hot weather, nor is the issue of prolonged hot weather addressed in current policy (McInnes et al. 2016). The Victorian Department of Health issues heat-health warnings that includes a caution to outdoor workers. For the weather forecast area that includes Melbourne, the heat-health warning threshold is an average temperature of 30 °C (i.e. the mean of the forecast daily maximum temperature and the daily minimum temperature for the following day) (Victorian Government Department of Health 2012). This is a very high threshold that is reached rarely. A number of other organisations also suggest thresholds at which extra care should be taken to avoid harmful health effects of hot weather, including sports organisations (Sports Medicine Australia 2007) and construction workers unions (Australian Workers' Union 2016; CFMEU Construction 2016). However, many use thresholds for action that are extreme temperatures, commonly 35 °C. Our findings suggest that in the case of consecutive days of heat, warnings should be given and prevention protocol initiated when temperatures lower than extreme temperatures are forecast, and well before extreme temperatures are reached. This is an important issue that should be addressed in OH&S regulations and guidelines. Australia continues to experience a warming trend, reflected in our data documenting the number of 2- and 3-day hot spells over the relatively short period of 10 years. It is notable that since this time, Australia as a whole has experienced its four hottest years, with 2013 being the hottest year on record (Australian Bureau of Meteorology 2016b; Australian Bureau of Meteorology 2017).

Conclusions

This study has found that workers in metropolitan Melbourne are at increased risk of work-related injury when exposed to consecutive days of hot weather with this effect becoming more pronounced as temperatures and duration of exposure increases. Temperatures at which health effect of exposure to sustained temperatures became evident were relatively moderate. We found the 70th percentile of daily maximum temperature (27.6 °C) to be the lowest temperature at which two and three consecutive hot days were associated with an increased risk of injury. Middle aged workers were found to be the most vulnerable age group, with this effect becoming apparent at ≥80th temperature percentile. This information contributes important evidence needed to inform OH&S guidelines, risk communication materials and other prevention strategies.

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